Comparing the embodied carbon and energy of a mass timber structure system to typical steel and concrete alternatives for parking garages

A. Zeitz[1], C.T. Griffin[2], P. Dusicka[3]

[1]*Soderstrom Architects, Portland, Oregon, United States*

[2]*Division of Arts and Humanities, The Pennsylvania State University, Altoona, Pennsylvania, United States*

[3]*Department of Civil and Environmental Engineering, Portland State University, Portland, Oregon, United States*

ABSTRACT: As operational energy use is minimized through high-performance design, construction and systems, the embodied carbon and energy from building materials and construction will play larger roles in the environmental impact of buildings. Consequently, the structural system should be a primary target for reducing the embodied carbon and energy of a building. Parking garages offer an ideal case study for comparing the embodied carbon and energy of different structural systems. As parking garages have little operational energy use outside and have few materials or systems, the embodied carbon and energy of the structure comprises a majority of the environmental impacts during its life-cycle. This study uses manual material take-offs from construction documents of four parking garages with one-way spans; one pre-cast concrete, one post-tensioned concrete, one cellular steel and one mass timber. The resulting comparison shows that there is little difference in the embodied carbon and energy of structural systems used for parking garages under best material practices. Mass timber, while more viable in a worst-practices scenario, loses its advantages when cement replacement and high recycled content steel are utilized.

KEYWORDS: structural system; life cycle assessment; material selection; wood products; glulam; cross-laminated timber; reinforced concrete; steel; parking garage; embodied energy; embodied carbon

1. INTRODUCTION

1.1 *Rationale*

The objective of this research is to determine whether the use of mass timber as a primary structural system provides measurable advantages over other common structural systems in regards to global warming impact (embodied carbon) and embodied energy, specifically in relation to above-grade parking garages. Although the automotive landscape is shifting with recent trends in mass transit, ride-sharing and self-driving vehicles, it is clear that cars and places to store them will remain a constant presence for the foreseeable future. This paper expands on a previous life-cycle analysis (LCA) by Griffin et al (2013) on the embodied energy of structural systems in parking garages. This paper uses an LCA of the embodied carbon and energy in the same three parking garages and the additional case study of a mass timber structure parking garage. Factors of similar seismic zones, design loads, column lengths and structural layouts remain valid points of consistency to ensure functional equivalence and accurate comparisons between structural systems. Mass timber is frequently touted as being more sustainable than comparable structural systems as evaluated from an embodied carbon standpoint (Kremer et al, 2015). Through the comparison of built projects inferred to be typical of their respective structural systems, this study seeks to evaluate the validity and magnitude of those claims in this specific typological use case.

Parking garages are an ideal case study for comparing the embodied energy and carbon of a variety of structural systems due to their minimal operational energy and limited materials or systems beside the structure. The embodied energy and carbon of the structural materials comprises a majority of the environmental impacts during this typologies' life cycle. As the urban population in the United States and globally is estimated to increase in the coming decades, parking garages will contribute significantly to the environmental impact of the built environment due to the high demand for automotive storage in both urban and suburban areas (Chester et al. 2010).

1.2 *Overview of embodied carbon and energy in building materials*

This paper uses embodied carbon and energy as a sustainability metric to compare structural systems as it can also serve as a good indicator of relative raw material depletion and general degradation of the natural environment when comparing alternatives (Ashley, 2009). A wide range of studies has looked at the embodied carbon and energy in building materials (Cabeza et al. 2013, Praseeda et al. 2015, Doh and Panuwatwanich 2014, Bontempi 2017), comparing the embodied and operational energy of buildings (Pacheco-Torgal et al. 2013, Ibn-Mohammed et al. 2013), overall LCA studies of buildings (Bansal et al. 2014, Cabeza et al. 2014, Chau et al. 2015, Karimpour et al. 2014, Stephan and Athanassiadis 2017) and comparing the embodied carbon and energy of structural systems (Cole and Kernan 1996, Griffin et al. 2010b, Goggins et al. 2010, Yeo and Gabbai 2011). The former being the focus of this paper. More recently several meta-analyses of the literature on embodied energy in buildings (Dixit 2017, Azari and Abbasabadi 2018) have noted significant variations in embodied energy values for building materials and whole buildings. These meta-analysis papers suggest a need for methodologies to assess the uncertainty of LCAs, more standardized measurement frameworks and the lack of transparent datasets.

1.3 *Life cycle inventory techniques*

LCA studies use one of three life cycle inventory techniques to derive embodied carbon and energy databases: process, input-output (IO), hybrid analyses. Goggins et al. (2010) and Azari and Abbasabadi (2018) summarize the relevancy, completeness and ease of application for each technique. Process-based analysis is conducted on specific materials or products with a system boundary set to define which inputs and outputs are considered in the life-cycle analysis. Process-based analysis generates results that can be used to compare buildings. Depending on where the boundary is set, truncation of upstream processes can occur in process analyses. This truncation will yield incomplete embodied impact values much lower than derived from other methods. IO analysis uses sector level data which can capture upstream impacts more completely but is only relevant to materials that are typical outputs of its sector and makes comparing buildings difficult. The hybrid approach uses both process and IO methods in different combinations, yielding more relevant and complete data, but requires significant manipulation of data and analysis to develop.

As the primary interest of this paper is ranking the environmental impact of structural systems used in parking garages, this paper uses the Inventory of Carbon and Energy (ICE) produced by the Sustainable Energy Research Team (SERT) at the University of Bath (Hammond & Jones, 2008) as the source for all embodied carbon and energy values. While not peer-reviewed itself, this inventory surveyed peer-reviewed articles from around the world on the embodied carbon and energy of construction materials and reports the average values found from these sources. The transparency of ICE is an advantage over other LCA datasets related to software, such has ATHENA or SimaPro that act like a "black box" and that may contain unstated assumptions or omissions (Plank 2008, Griffin et al. 2010b, Robertson et al. 2012). Many of the issues that Dixit (2017) highlights with embodied energy datasets are present in ICE, including inconsistent system boundaries, different electricity fuel mixes in each country, lack of completeness and accuracy to name just a few. As the ICE values are averages of varying life cycle inventory analyses, studies have shown that the embodied energy values developed in this paper are likely lower than if more complete hybrid analysis-based datasets were used to avoid truncation error (Crawford 2008, Crawford 2011, Crawford and Stephan 2013, Stephan and Stephan 2014). Consequently, the embodied carbon and energy values generated in this paper should only be used to compare the embodied impacts of one structural system to another and not to compare the embodied impacts to operational impacts.

For the purposes of this paper, embodied energy is defined as the total primary energy consumed during resource extraction, transportation, manufacturing and fabrication of construction materials, known as "cradle-to-gate" or initial embodied energy. This is distinct from the "cradle-to-grave" method of calculating embodied energy which would also include primary energy expended on the transportation, construction, maintenance and disposal of building materials. As transportation, construction methods, building maintenance, useful life, and demolition can vary greatly (O'Connor 2004, Junilla et al. 2006, Dixit 2017), this paper focuses on the more consistent and quantifiable components of the embodied carbon and energy of structural materials. Embodied carbon is defined within the context of this paper as inclusive of the carbon stored within the material itself and emitted as a by-product of the manufacturing process of said material. Like embodied energy, this is confined to a "cradle-to-gate" scope for the purposes of this research.

1.4 *Advantages of parking garages as comparators for structure level LCAs*

An LCA study of two theoretical, five-story office buildings, one with a steel frame and concrete slabs and the other with a cast-in-place concrete structural system, showed similar energy use during construction, operation and end-of-life (Guggemos and Horvath 2005). However, the energy used in these steel and concrete structures differed most significantly in the "cradle-to-gate" manufacture of the building materials. Instead of office buildings typical of theoretical and case study based whole building LCA studies, this paper uses parking garages to avoid the variance found in and across office building LCA studies. While numerous studies have calculated the embodied energy of theoretical office buildings (Cole & Kernan 1996, Scheuer et al, 2003), it is difficult to apply the results of these studies with uniform grids to the design of a new building due to the unique requirements of each new site and program that making using a similar standardized grid impossible. Due to a wide range of assumptions, it is even difficult to compare one theoretical office building LCA study to another (Robertson, et al. 2012). Furthermore, when the size of the building and material used is held constant, the embodied energy of a structural system when divided by the total floor area (MJ/m^2) can still vary by up to 50% depending on the building (Suzuki & Oka 1998). Consequently, using case studies of office buildings to compare alternative structural systems has limited accuracy. As parking garages have predictable loads, consistent floor-to-floor heights and accommodate exactly the same program, there should be fewer variables distorting comparisons between different structural systems. This paper uses real, built parking garages rather than a theoretical design to study the effects of irregularities that develop due to site constraints typical of urban infill projects. One major difference between parking garage structures and those used in office buildings is that garages typically use long one-way spans to create clearances for a driving lane and a row of parking on either side. Office buildings typically use two-way concrete systems or shorter span steel bays.

2. METHODOLOGY

2.1 *Structure selection*

The precast concrete, cellular steel and post-tensioned concrete designs and data analysis were inherited from the previous study by Griffin et al. (2013). These parking garages were selected from a survey of ten different parking garages for their regular layouts and absence of composite structural systems. The mass timber parking garage that was studied as part of this research was designed by SRG Partnership and KPFF Consulting Engineers for the City of Springfield, Oregon. The mass timber garage falls within the same seismic zone as the previously selected parking garages and has comparable soil conditions. Though not selected using the same criteria as the previous analysis the mass timber parking garage was considered to be sufficiently comparable to this existing data set to generate meaningful comparison as can be seen in Table 1.

Table 1. Parameters of parking garages used in this study

Primary Span	*Stories*	*Area* m^2 (ft^2)*	*Typ. Span* m (ft)	*Typ. Story* m (ft)	*Soil Bearing* kPa (lb/ft^2)
Precast Concrete	3	12,300 (132,000)	17.1 (56.0)	3.4 (11.0)	216 (4,500)
Cellular Steel	4	13,300 (143,000)	17.9 (58.75)	3.4 (11.0)	240 (5,000)
Post-Tension Conc.	4	29,100 (313,000)	18.5 (60.5)	3.4 (11.0)	240 (5,000)
Mass Timber	4	19,900 (214,000)	18.3 (60.0)	3.4 (11.0)	240 (5,000)

2.2 *Description of selected structural systems*

The mass timber garage is roughly rectangular with overall dimensions of 196 ft by 266 ft. It is comprised of a reinforced concrete ground floor and foundation and three levels of composite CLT and concrete decking supported by a series of post-tensioned glulam beams and columns. Lateral load resistance is provided by a number of post-tensioned CLT walls around the centralized ramps of the design. While the fourth floor is capped with a steel structure that carries an array of photovoltaic panels, these components have been omitted from the comparison calculations though the sizing of the remaining structural members accounts for this additional load. This decision was made under the assumption that a similar steel structure could be grafted to any of the parking garages used in this study. All material calculations used in this study are derived from the construction drawings provided by SRG Partnership.

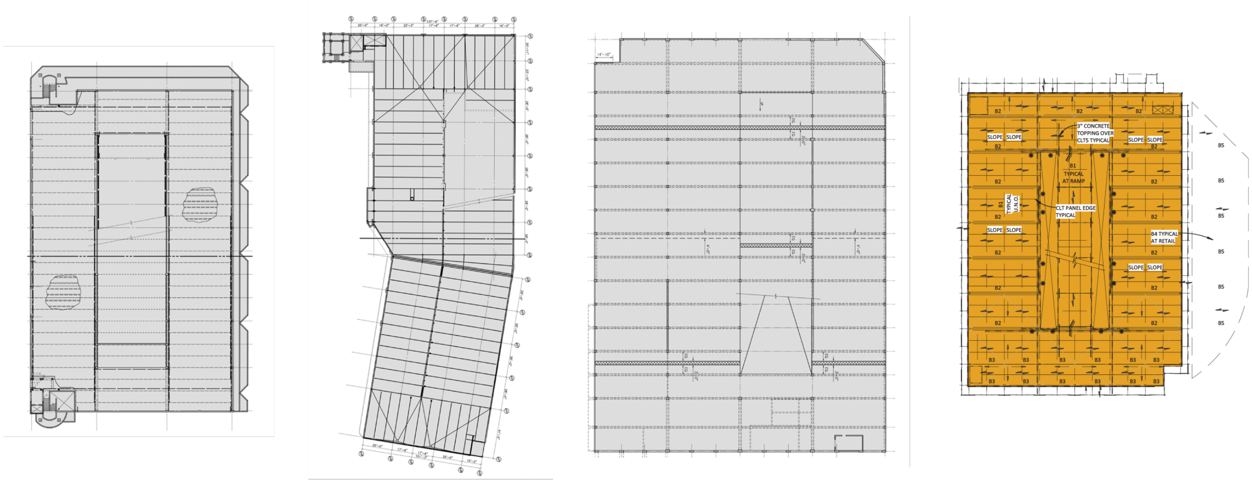

Figure 1. Plans at the same scale of the case study parking garages (left to right): precast concrete, cellular steel, post-tensioned concrete and mass timber

2.3 *Data collection*

A digital copy of the structural drawing set was used as the primary source of information from which the mass timber parking garage calculations were derived. Calculations for the precast concrete, cellular steel and post-tensioned parking garages were taken from the previous study by Griffin, et al. (2013). Structural bay takeoffs for the three garages of the previous study were based on physical copies of the structural drawing set for each respective building. Due to the amount of data collected these detailed calculations are only summarized here in this paper.

In an effort to maximize direct comparison to the findings of the previous paper this research used an identical methodology. Throughout the data collection process all values and quantities reflected the specifications stated within the provided drawings. As such, all calculations are based on the assumption that during the construction process specifications were met precisely while the actual dimensions and strengths of the built projects could differ from design drawings. For example, the assumption is made in this study that all materials do not exceed the stated minimum strength when it is a requirement that would likely be exceeded in practice. Where measurements proved difficult rules of thumb were used, such as calculating steel weight as a percentile of the overall concrete weight it reinforces. Wherever possible, exact measurements were taken from the drawings to account for all of the structural materials in each parking garage. These materials were totaled by breaking down the types of structural materials used for each garage, such as different strengths of concrete, reinforcing bar, structural steel sections, etc. Each of these material totals was multiplied by the embodied carbon and energy factors from the ICE Database. For each parking garage, this was done for two scenarios: (1) a worst-case scenario assuming no recycled content in any steel and no cement replacement in concrete and (2) a best-case scenario assuming the most likely case for the maximum cement replacement and recycled steel. Material, embodied energy and embodied carbon totals were divided by the total parking area of each garage in order to compare the systems used in the case studies to one another. This methodology was repeated at the scope of a single structural bay approximately 36 m by 18 m (120 ft by 60 ft) in area for each garage to facilitate a means of material comparison that was not reliant on dividing the weight of material or environmental impact for an entire parking garage structure by the total floor area to make comparisons. This is similar to the method of using structural bays to estimate the environmental impact of structural systems developed in Griffin, et al. (2010b).

2.4 *Embodied energy and carbon of structural materials*

As stated in Section 1.3, this study uses cradle-to-gate embodied energy and carbon values from the ICE database (Hammond and Jones, 2008). The values used for concrete materials can be found in Table 2, steel materials can be found in Table 3 and wood materials in Table 4. It should be noted that this version of the ICE database lacks collected data for CLT products, this study assumes the presented values for glulam to be comparable for representing a similar distribution and ratio of wood and adhesive. These values are extrapolated from worldwide averages in the ICE database and focused on the implications for the United Kingdom. Consequently, these values are not reflective of the specific conditions and primary energy sources used in the Pacific Northwest of the United States. Materials are calculated in both best and worst use case scenarios. Best case is defined as the most likely case for maximum use of cement substitute in concrete mix and percentile of recycled content in steel composition. In the case of mass timber specifically, (bio) carbon is not included as part of the best-case calculations as this accounts for the carbon naturally sequestered through the growing process. This aligns with the Intergovernmental Panel on

Climate Change (IPCC) determination that the emissions from biomass-based material are effectively carbon neutral. As this determination is not fully accepted, (bio) carbon is included in worst case calculations for mass timber. Worst-case is defined as material derived from a completely raw or virgin state. While the latter is unlikely to occur in common construction practice the difference between these two scenarios is strong evidence to advocate the implementation of best practice material sourcing as a consistent design strategy.

Table 2a. “Cradle-to-gate” embodied energy (MJ/kg) of structural concrete with various portland cement replacement rates with fly ash. Data extrapolated from ICE (Hammond and Jones 2008)

MPa (PSI)	*0% Fly Ash*	*25% Fly Ash*	*50% Fly Ash*
27.6 (4,000)	0.834	0.727	0.620
31.0 (4,500)	0.877	0.772	0.667
34.5 (5,000)	0.899	0.814	0.770
41.4 (6,000)	1.020	0.895	

Table 2b. “Cradle-to-gate” embodied carbon (kgCO_2e/kg) of structural concrete with various portland cement replacement rates with fly ash. Data extrapolated from ICE (Hammond and Jones 2008)

*PSI***	*0% Fly Ash*	*25% Fly Ash*	*50% Fly Ash*
27.6 (4,000)	0.132	0.262	0.216
31.0 (4,500)	0.138	0.264	0.223
34.5 (5,000)	0.141	0.267	0.225
41.4 (6,000)	0.148	0.273	0.233

Table 3a. “Cradle-to-gate” embodied energy (MJ/kg) of virgin and 93% recycled structural steel products. Data extrapolated from ICE (Hammond and Jones 2008)

Material	*0% Recycled Content*	*93% Recycled Content*

Structural Sections	34.9	10.9
Decking (Cold Formed Galvanized)	36.6	11.5
Reinforcing Bar	27.3	9.5
PT Tendons	32.5	10.3

Table 3b. "Cradle-to-gate" embodied carbon ($kgCO_2e/kg$) of virgin and 93% recycled structural steel products. Data extrapolated from ICE (Hammond and Jones 2008)

Material	*0% Recycled Content*	*93% Recycled Content*
Structural Sections	3.03	0.58
Decking (Cold Formed Galvanized)	3.01	0.58
Reinforcing Bar	2.77	0.61
PT Tendons	3.02	0.59

Table 4a. "Cradle-to-gate" embodied energy (MJ/kg) of worst case and best practice mass timber products. Data extrapolated from ICE (Hammond and Jones 2008)

Material	*Worst Case*	*Best Practice*
Glulam	4.91(bio)+7.11(fos)	7.11(fos)
*Cross Laminated Timber**	4.91(bio)+7.11(fos)	7.11(fos)

* ICE 2008 lacks entries for CLT, this study assumes glulam values as being approximate substitutes

Table 4b. "Cradle-to-gate" embodied carbon ($kgCO_2e/kg$) of worst case and best practice mass timber products. Data extrapolated from ICE (Hammond and Jones 2008)

Material	*Worst case*	*Best Practice*
Glulam	0.45(bio) + 0.42(fos)	0.42(fos)
*Cross Laminated Timber**	0.45(bio) + 0.42(fos)	0.42(fos)

* ICE 2008 lacks entries for CLT, this study assumes glulam values as being approximate substitutes

3. RESULTS

3.1 *Structural material quantities*

Using the same methodology as in the prior study by Griffin et al. (2013), every structural component in the mass timber case study was accounted for using manual take-offs checked by at least two authors. Following this the total amount of concrete, steel and wood was divided by the total parking area of the structure for direct comparison against the previous three garage case studies (Figure 2). Despite being the second largest of the four garages (Figure 1) in the comparison, the mass timber design utilizes the least amount of overall material. As noted previously, the steel value listed here is representative of concrete reinforcing, structural connections and other minor structural elements but does not include the photovoltaic roof superstructure located on level 4.

Concrete accounts for a majority of the weight in the mass timber structural system due in part to its composite use with CLT to form the decking for levels 2, 3 and 4, this is expanded upon in Section 4.1. Structural members are almost entirely comprised of wood, and the lighter weight of the wood limits its contribution to the overall weight of the structural system. Although the weight per unit area of the wood used in the mass timber structural system is greater than that of steel in the cellular steel structural system, the amount of concrete used in the cellular steel structural system is 59% greater making the mass timber system the lightest overall.

Figure 2. Structural material weight per unit area (kg/m^2)

3.2 *Structural bay material quantities*

A second series of material takeoff were conducted manually on all four of the case study garages using a predefined series of typical structural bays for each garage. In all cases these bays were located above the ground floor and not inclusive of lateral load resisting elements such as shear walls, moment frames or cross bracing. This facilitated a means of direct material weight comparisons for gravity loading between similar designs without needing to divide by total parking area. Additionally, this more granular level of analysis highlighted other variables, such as beam depth, as points of comparison between the respective structural systems.

As shown in Figure 3, concrete accounts for the majority of material weight in all studied garages. While similar to the weights shown previously this comparison derived from above grade levels and is not inclusive of foundation concrete. Unsurprisingly, the two concrete based span system garages are noticeably heavier. The ratio of wood to concrete in the mass timber garage becomes more equalized, this is noteworthy as the only concrete included in this calculation is a 3” topping slab set atop the CLT decking. A typical structural bay in this garage has roughly the same mass of wood as concrete. Lastly the steel to concrete ratio of the cellular steel garage is also less drastic than what was present in the areal density, suggesting a substantive amount of the overall mass for that design resides in the foundation concrete.

Table 4. Parameters of parking garages structural bays used in this study

Primary Span	*Bay Dimension (m x m)*	*Total Weight (kg)*	*Area (m^2)*	*Beam Depth (mm)*
Precast Concrete	36.6 x 17.1	319,000	5.2	813
Cellular Steel	34.2 x 17.9	172,000	5.4	678
Post-Tension Conc.	35.8 x 18.5	370,000	5.6	914
Mass Timber	36.6 x 18.3	231,000	5.58	914

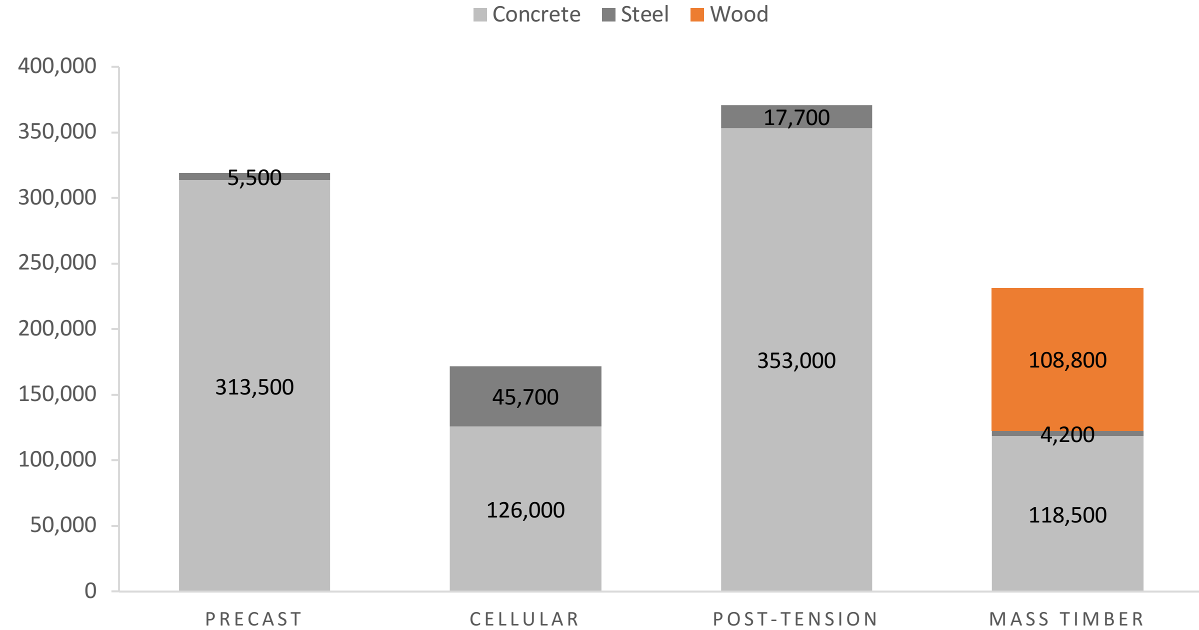

Figure 3. Structural bay weight by material (kg)

3.3 *Embodied energy of structural systems*

The total embodied energy for the mass timber garage was calculated from each of its constituent materials twice, once using values for virgin material and once using values for the highest conceivable replacement of cement, recycled content in steel and omitting (bio) energy components. Values for the precast, cellular and post-tension garages are taken directly from the previous study by Griffin et al. (2013). Table 5 outlines the range of embodied energy as impacted by these means of material implementation. The mass timber garage presents embodied energy values within the range established in the previous study, overall values are comparable falling toward the higher end in both use case scenarios. Likewise, percent reduction in embodied energy between worst and best practices falls within the established data range.

Table 5. Total “cradle-to-gate” embodied energy of each case study

Primary Span	*Area(m^2)*	*Worst Practices (TJ)*	*Best Practices (TJ)*	*Reduction in Embodied Energy*
Precast Concrete	12,300	16.0	10.5	34%
Cellular Steel	13,300	30.8	12.7	59%
Post-Tension Conc.	29,100	42.3	24.7	42%

Mass Timber	19,900	32.85	19.28	41%

These calculations do not take into account the overall size of the respective structures. In order to directly compare the sustainable impact of each system their embodied energy was divided by the total parking area of each garage (Table 6). Again, the values for the three previous case studies are inherited and as shown in that study the steel garage presents the most dramatic shift in embodied energy between worst and best practice material application. The embodied energy for mass timber values are comparable to the other structural systems in both worst and best practice implementation scenarios. See section 4.1 for additional comments and discussion.

Table 6. "Cradle-to-gate" embodied energy of each case study per unit floor area (MJ/m^2)

Primary Span	*Worst Practices*	*Best Practices*
Precast Concrete	1,300	860
Cellular Steel	2,300	950
Post-Tension Conc.	1,500	850
Mass Timber	1,652	970

3.4 *Embodied carbon of structural systems*

Although not included in the prior study this research expanded the scope of the case studies to include embodied carbon as another means of potentially delineating the environmental impacts of each respective structural system. Embodied carbon is defined in this context as the carbon that comprises the material of the system itself as well as the carbon that is emitted from the related manufacturing processes to produce it. Similar to embodied energy, the total embodied carbon was calculated twice for each garage. Again, once using values for virgin materials and once using values for the highest conceivable replacement of cement and recycled content in steel and subtracting the carbon naturally sequestered by wood based products. Table 7 outlines these results, once again the difference between virgin and high-recycle content steel is the most substantial gain. Overall however the structural systems are fairly similar in their capacity to improve through the use of best implementation practices.

Table 7. Total "cradle-to-gate" embodied carbon of each case study

Primary Span	*Area(m^2)*	*Worst Practices ($kgCO_2e$)*	*Best Practices ($kgCO_2e$)*	*Reduction in Embodied Carbon*
Precast Concrete	12,300	2,166,000	1,412,000	35%
Cellular Steel	13,300	3,146,000	1,216,000	61%
Post-Tension Conc.	29,100	5,133,000	2,942,000	43%
Mass Timber	19,900	2,924,000	1,579,000	46%

As before these calculations do not take into account the overall size of the respective structures. In order to directly compare the sustainable impact of each system their embodied carbon was divided by the total parking area of each garage (Table 8). Mass timber is consistently lower in embodied carbon compared to the other structural systems in both near virgin and high-recycled and cement replacement implementations.

Table 8. Total "cradle-to-gate" embodied carbon divided by total parking area ($kgCO_2e/m^2$) for each case study

Primary Span	*Worst Practices*	*Best Practices*
Precast Concrete	80	52
Cellular Steel	107	41
Post-Tension Conc.	80	46
Mass Timber	67	37

4. DISCUSSION

4.1 *Design limitations of mass timber*

The research and analysis within this paper is largely derived from the methodology utilized by Griffin et al. (2013). The inference that parking garages provide an idealized model for comparison of structural systems was inherited for this paper and assumed to be true throughout the research process. However, the resulting embodied energy comparisons from both the overall building and the predefined structural bay takeoffs were surprisingly unfavorable toward the use of mass timber over other structural systems, prompting further investigation into likely causes. The first foreseeable issue is the use of concrete slab over CLT decking throughout the mass timber garage. This application is presumably in relation to the exposed nature of the structural system in an open-air parking garage and to limit degradation from regular vehicular use. This concrete decking accounts for over half of the overall weight of concrete present within the design and increases load on and sizing of the CLT and glulam structural members as consequence. It is not known if the inclusion of this concrete is derived from code-based requirements, conservative design practices in response to less commonly used material, or some combination of these and other factors. What is evident is that this decision is specific to the building typology and as such diminishes the applicability of the embodied energy findings to other structural typologies.

This plays into the second issue of mass timber being regarded as more sustainable based upon direct comparison of equivalent volumes of material. Such comparisons become muddied in the real-world use case of a building which will never be wholly comprised of a singular material. This is particularly evident in the case of the mass timber garage used for this study wherein the weight of reinforced concrete used is nearly 3.5 times greater than the weight of the wood. This presence of other materials as a necessity of contemporary design and constructions limits the direct impact of using mass timber as a means of reducing overall embodied energy and embodied carbon. This is perhaps a factor that could be overcome as mass timber becomes more widely adopted and as relevant design criteria are made more efficient through regular use.

Finally, all calculations of embodied energy and embodied carbon used within this paper are reliant on values taken or extrapolated from the data presented in the 2008 ICE database (Hammond and Jones, 2008). This methodology was deemed suitable in the case of the previous study by Griffin et al. (2013) and subsequently inherited for this study. This is problematic primarily in regards to the limited mass timber data set from which ICE has generated its values and the complete absence of any CLT specific data. This factor is not wholly unexpected due to the relatively recent introduction of mass timber as common structural system. The limited gains in embodied energy between worst practices and best practices for mass timber could be attributed to insufficient data relative to this specific material choice. At the time of this writing a new iteration of the ICE database is due to be published which could potentially be a driver for revisiting the findings presented here.

4.2 *Similar findings and further interpretations*

While unanticipated, the relatively high embodied energy values for mass timber in relation to other structural materials found in this study does align with previous work by Robertson et al. (2012). In this paper, an LCA was conducted on both a built mid-rise concrete structure office building and a synthetic recreation of the same building using a mass timber structure. There comparison found the embodied energy of the mass timber design to be substantially higher than the concrete structure (by almost 80%) when inclusive of both feedstock and process energy. Robertson et al. goes on to specify the delineation between process and feedstock energy is crucial in that the former accounts for the manufacturing of the specific material while the latter is a summation of the potential energy embodied within the material. They note that the embodied energy of mass timber is predominately feedstock based, indicating the presence of easily attainable energy at the end of the materials service life as a combustible fuel source. This suggests that the higher embodied energy values of mass timber are not necessarily an indicator of an environmentally inferior structural material. Although this paper utilized built parking garages as the subject of study the embodied energy was derived from a standardized database rather than direct sourcing information. As such the results are arguably more directly comparable but unfortunately lack the granularity of process and feedstock energy delineation. Even so, the conclusion found by Robertson et al. remains valid to the analysis of mass timber through embodied energy comparison.

5. CONCLUSIONS

This research sought to determine whether the use of mass timber as a primary structural system provides measurable advantages over other common construction systems in regards to global warming impact, specifically in relation to surface parking garages. This study shows that mass timber currently presents marginal gains in embodied carbon and energy performance between outlined worst and best practices. These gains are well within the 30% margin of error in the ICE database. In comparison to previous studies of structural systems used within the same typology, mass timber presents comparable impact performance with standard steel and concrete structural systems.

While mass timber as a structural *material* shows promise as a lighter weight, carbon storing, renewable alternative to steel and concrete, this study has shown that the design of the structural *system* and material choices in the system can negate some of these advantages. For example, Figure 3 shows the gravity loading system for the mass timber parking garage as designed is 34% heavier than the one that uses steel. Further, the environmental benefits of using mass timber rely on forest practices, milling and manufacturing that must release less greenhouse gases than stored in the wood and studies such as those by Puettmann and Wilson (2005) and Bergman and Bowe (2008) show that this environmental impact can vary greatly.

Similar to the findings in Griffin et al. (2013), architects and engineers can reduce the environmental impact of structural systems the most by the appropriate specification and curation of best-case material practices, such as using high recycled content steel, cement replacement and sustainably harvested wood. Mass timber is a viable alternative to more common steel and concrete structural systems. To achieve significant improvements in environmental impact, mass timber structural systems will have to be designed to minimize the use of concrete and steel. Mass timber structural systems are highly subject to design choices, and its implementation does not provide the single source solution to greenhouse gas emissions in building construction that it is frequently advertised to be.

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