Quantifying Environmental Impacts of Structural Material Choices Using Life Cycle Assessment: A Case Study

Don Davies, P.E., S.E. [1]

Leif Johnson, P.E., S.E.[2]

Blake Doepker, P.E., LEED AP BD+C[3]

Meagan Hedlund, P.E., LEED AP BD+C[4]

[1]President, Magnusson Klemencic Associates, 1301 Fifth Avenue, Suite 3200, Seattle, Washington 98101; Phone: (206) 292-1200; email: ddavies@mka.com

[2]Senior Associate, Magnusson Klemencic Associates, 1301 Fifth Avenue, Suite 3200, Seattle, Washington 98101; Phone: (206) 292-1200; email: ljohnson@mka.com

[3]Senior Design Engineer, Magnusson Klemencic Associates, 1301 Fifth Avenue, Suite 3200, Seattle, Washington 98101; Phone: (206) 292-1200; email: bdoepker@mka.com

[4]Design Engineer, Magnusson Klemencic Associates, 1301 Fifth Avenue, Suite 3200, Seattle, Washington 98101; Phone: (206) 292-1200; email: mhedlund@mka.com

Handling editors: Alice Moncaster, Francesco Pomponi

Abstract

The significance of environmental impact quantification for various structural materials is increasingly important for structural engineers to both understand and communicate to others. Building owners and architects are beginning to request this data in the form of a Life Cycle Analysis (LCA), so that the environmental impacts of structural materials from harvesting to processing and beyond can be reported as accurately as possible to an audience interested in more environmentally responsible buildings. Recently, there has also been added motivation in the United States to follow a trend in Canada and Europe to construct more structures out of mass timber products, such as Cross-Laminated Timber (CLT) or Nail-Laminated Timber (NLT). Companies market these mass timber products as viable, sustainable options to compete with conventional steel and concrete construction.

Mass timber buildings are commonly perceived as more environmentally responsible than buildings with concrete and steel framing, but very few have attempted to accurately quantify the environmental impacts of this claim, or to prove if the hype is indeed correct.

This paper reports the findings of a case study investigation on the above, a seven–story, 85-foot tall new construction office building. The case study focuses on comparing the "reported industry average" structural embodied carbon impacts between four different framing system combinations that include mass timber, steel, and concrete, using the GaBi database within the LCA software "Tally." The limitations of this study are discussed including differences between the LCA datasets used for each material. The goal of this paper is to develop a comparison utilizing current LCA tools readily available, to highlight the variabilities within that comparison, to assess if an accurate comparison can indeed be made, and to make observations on what are the most critical variables in structural embodied carbon impacts for this building. The ultimate objective is to help advance the reliability of future LCA studies.

Life Cycle Analysis History and Limitations

Environmentally-focused LCA took a major step forward in the 1990s, when the International Organization for Standardization (ISO) defined its ISO 14040 series, providing a general LCA approach. ISO 14044 defines LCA as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle." LCA methods have also been formalized by the British Standards Institute's PAS 2050, the World Resources Institute Protocols, and ISO 14067 (Skone, 2013).

In the United States, the American Society of Testing and Materials (ASTM), the International Building Code (IBC), the American Society of Civil Engineers/Structural Engineering Institute (ASCE/SEI), and the Council on Tall Buildings and Urban Habitat (CTBUH) have all initiated environmental LCA working groups. Most recently, the Athena Sustainable Materials Institute defined LCA as "a scientific method for measuring the environmental footprint of materials, products, and services over their entire lifetime" (Athena SMI, 2016).

Green rating systems, including USGBC LEED v4, the Living Building Challenge (LBC), IgCC, calGreen, and others have all recently included whole–building LCA elements within their ratings. Architecture 2030's Challenge for Products and the Carbon Leadership Forum are organizations spearheading the application of LCA to the USA building industry.

While there is considerable activity around the topic—most of it well intentioned and with the ultimate hope of reducing the speed of global warming—there is no consensus on how best to use LCA principles and data. The green rating systems also do not yet provide consistent guidance for how LCA should be fully executed within their standards. Many practitioners who attempt to track carbon emissions for upcoming or completed projects also find the data sometimes inaccessible or inconsistent or the processes to evaluate the data difficult to implement.

LCA is an evolving field and it would be misleading to imply that all involved parties have the same objectives. However, there are more common themes and activities than differences. To mitigate the impacts of building design on the environment and global warming, LCA has the potential to transform many of our design and decision-making processes. As the impacts from global warming increase, LCA evaluations become an effective method to answer public comments with credible scientific and quantified data in ways not previously possible.

There are several LCA terminologies that are useful to understand:

- LCA provides quantified data of the environmental impacts of a building design within a defined study boundary. The data includes environmental impacts such as global warming, ozone depletion, land/water acidification, eutrophication, tropospheric ozone, and non-renewable energy use (U.S. Green Building Council, 2013).
- Product Category Rules (PCRs) are guidelines that define industry-specific measurements for the purpose of producing an Environmental Product Declaration (EPD). PCRs provide the structure needed to report the results of EPDs and are typically developed with the input of the industry trade organizations which the PCR covers (Carbon Leadership Forum, 2015).

- An EPD declares the environmental impacts of a product over its expected life, similar to a food nutrition label. An EPD should be third-party verified and made public upon completion. An EPD and the respective PCR should, at a minimum, be compliant with ISO 14025 and 21930 and be posted in their entirety (see Figure 1).

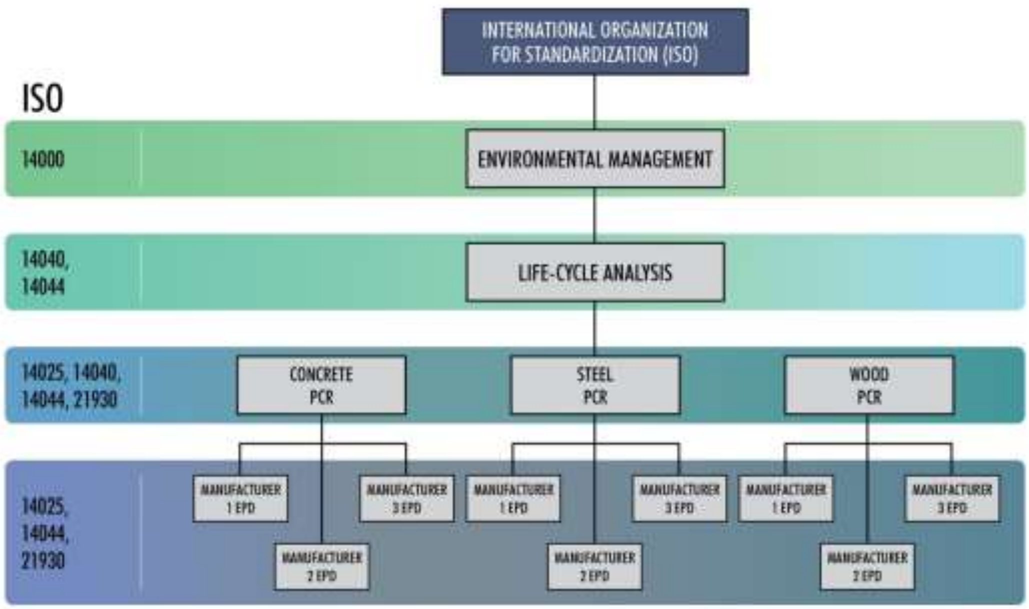

Figure 1. Relationships between ISO Standards, LCA, PCRs, and EPDs

Herein resides one of today's fundamental challenges with LCAs. The industry- and material-specific PCRs are often not cross-compatible, as they do not always use the same boundary conditions or consider variables in the same way. Even LCA experts knowledgeable about the differences cannot always make practical comparisons between differing materials.

ASTM recently published a standard, ASTM E2921-16, to try to tackle this issue. It presents the minimum criteria for comparing whole building life cycle assessments. However, it only applies to comparative assessments of a baseline building with a modified one for the purposes of an LCA study. As an example of the challenge, it is difficult to directly evaluate timber land use issues against steel and concrete environmental impacts. This is a significant issue that is yet to be addressed with industry consensus, but is fundamental to any credible whole building LCA comparative studies between material types.

Attempting a whole-building LCA with today's data sets can be approached through a strategy of reducing the number of variables considered and focusing on the most significant environmental impacts as a means of getting closer to more comparable results. While not perfect, by looking at statistical correlations and percentage reductions of singular largest impact variables from one option to another, reliable data can often be achieved to allow for more informed decision making. Such focus begins to bring clarity to data comparisons within the design and decision-making processes. While LCA often requests and reports data from multiple impact categories, analyzing the Global Warming Potential (GWP), often defined as the embodied carbon of a design, is perhaps the most understood and meaningful of these variables, and has thus been the focus of this study.

LCA studies that focus on GWP and consider the relative impact of system choices and optimization studies within the same collection of materials are some of the most meaningful LCA studies to date. Within the building industry, prior LCA studies by Magnusson Klemencic Associates (MKA) and others have also shown that the structure is typically the single largest component of the embodied-carbon footprint for new construction projects, provided the building itself is the only consideration and ignoring building use (Mahler and Schneider 2016, Davies et al. 2014). Given the limited number of materials and industries that produce the structural frame for buildings, and with LCA focusing on optimizing those materials and reducing their production carbon footprints, the structure becomes a high-value investment of time and effort for current LCA discussions and comparisons.

The life cycle stages included in the scope of an LCA is important to define. Two common examples are referred to as "Cradle to Gate" and "Cradle to Grave". Cradle to Gate encompasses the material extraction and product manufacturing up to the factory gate. Meanwhile, Cradle to Grave includes the Cradle to Gate environmental impact while also including the environmental impact of the material during construction and through to its end of life. While more globally conclusive, a Cradle to Grave LCA typically involves speculation on the future so its accuracy is often more debated than the Cradle to Gate study. It is an attempt, though, for closedloop considerations of all impacts. Whether the Cradle to Grave impacts of recycling, depositing in a landfill, or end of life decomposition/incineration are captured in an LCA depends on the governing PCR for the materials considered, and is a point of inconsistency between many current PCR's. Standardization around this topic is an area for future work.

LCA Software Used for Study

Numerous software tools are currently available for completing LCAs. Of these, Tally is used for the purpose of this case study. Tally is a recently released LCA module for Autodesk Revit® and its goal is to help to streamline the process of quantifying the environmental impact of building materials for whole-building analysis as well as comparative analyses of design options. While working on a Revit model, the user can define relationships between Building Information Modeling (BIM) elements and construction materials from the Tally database, which relies on the GaBi databases (2013 LCI: http://www.gabi-software.com/international/databases/gabi-database/) from Thinkstep.

Tally does not provide the ability to directly model LCA data for anything other than products specified within its database. This limitation, however, controls the quality and reliability of the LCA data reported. While the database is extensive and growing, there exists a limitation when attempting to identify project-specific and unique material traits, such as concrete mix designs. Tally can, however, output a bill of quantities to an Excel spreadsheet, allowing for data manipulation outside of the program at later project stages.

Case Study Parameters

The building used for this case study includes seven above-grade floors, with one floor of below grade parking. The height of the building is 85 feet above grade, and has approximately 290,000 square feet of floor space. The occupancy is mostly office with retail at the ground level. The building itself is located in a low seismic region where wind controls the lateral design, with a basic wind speed of 90 mph per ASCE7-05. The foundation used for all four gravity systems is an array of spread footings with conventional slab on grade, which was based on a bearing pressure of 10,000 psf. Note that, while the foundation was included for each building configuration in this study, they were not uniquely designed for each gravity system. Given the relatively high bearing pressure of the site and minimum foundation system dimensions that would not change between gravity systems (such as basement wall height, or building footprint area), this was not seen as an area of significant difference between the options studied. This may not be the case, though, at sites with poorer soil conditions.

The lateral system is a concrete core for each of the designs considered. This choice allowed for a consistency of variable control between designs, including impacts from architectural programing of the building core program.

The following structural gravity systems were selected for comparisons of their embodied carbon and are illustrated in Figures 2-5:

- **Design A**: Glulam beams and columns with Nail Laminated Timber (NLT) flooring,(including a concrete topping slab for acceptable vibration and acoustical performance) above grade, with a mildly reinforced concrete slab at level 1 and 2 with concrete columns below level 2.
- **Design B**: Steel beams and columns with 3” concrete slab on 3” corrugated metal deck above grade, and 10” mild concrete slab at level 1 with concrete columns below grade.
- **Design C**: 8” post-tensioned concrete slabs above grade, 10” mild concrete slab at level 1 with concrete columns.
- **Design D**: 10” mild concrete slabs with concrete columns.

All three designs were fully designed and modeled in separate Revit models. Using Tally, specific materials and reinforcing quantities were defined for each of the structural elements, which allowed the software to capture the embodied environmental impacts in the concrete, steel, and timber elements. Concrete mixes were industry standard (as defined in the Tally database) and not carbon optimized for the design of this building. Appendix A summarizes material quantities for each design. The embodied global warming potential of non-primary structure, such as structure to support mechanical systems, exterior enclosure, architectural components and secondary finishes (i.e., exposed wood ceiling versus dropped ceilings), as well as any secondary structure required to support these elements, were not considered within the scope of this study.

The building was analyzed for a 60 year life cycle. Tally includes Stage D (reuse, recovery and recycling) in its Cradle to Grave analysis, which is sometimes only included in other LCA's Cradle to Cradle scopes. To be consistent with Tally's definitions, "End of Life" includes Stage D and is included in the Cradle to Grave analysis.

Tally includes the following life cycle phases for its data per ISO 14040 and 14044:

Product Manufacturing:

- A1: Raw material supply,
- A2: Transport (raw materials to the location where the product is manufactured)
- A3: Manufacturing

Construction:

- A4: Transportation (between manufacturer and building site)
- A5: On-Site Construction

Building Use:

- B2: Maintenance
- B3: Repair
- B4 Replacement
- Note: life cycle phases B1 (use), B5 (refurbishment) and B6 (operational energy) are outside the scope of Tally and were not included in this study. At the time of the study, life cycle phase B6 (operational energy) was not built into Tally, and thus was also outside the scope of this study.

End of Life:

- C2: Transport
- C3: Waste Processing
- C4: Disposal

- Note: Life cycle phase C1 (demolition) is not included in Tally's database and was outside the scope of this study.
- D: Reuse, recovery, and recycling potential

"Cradle to Gate" comparisons were also investigated. This includes life cycle phases A1-A3 as defined above.

The following figures summarize the different structural systems investigated.

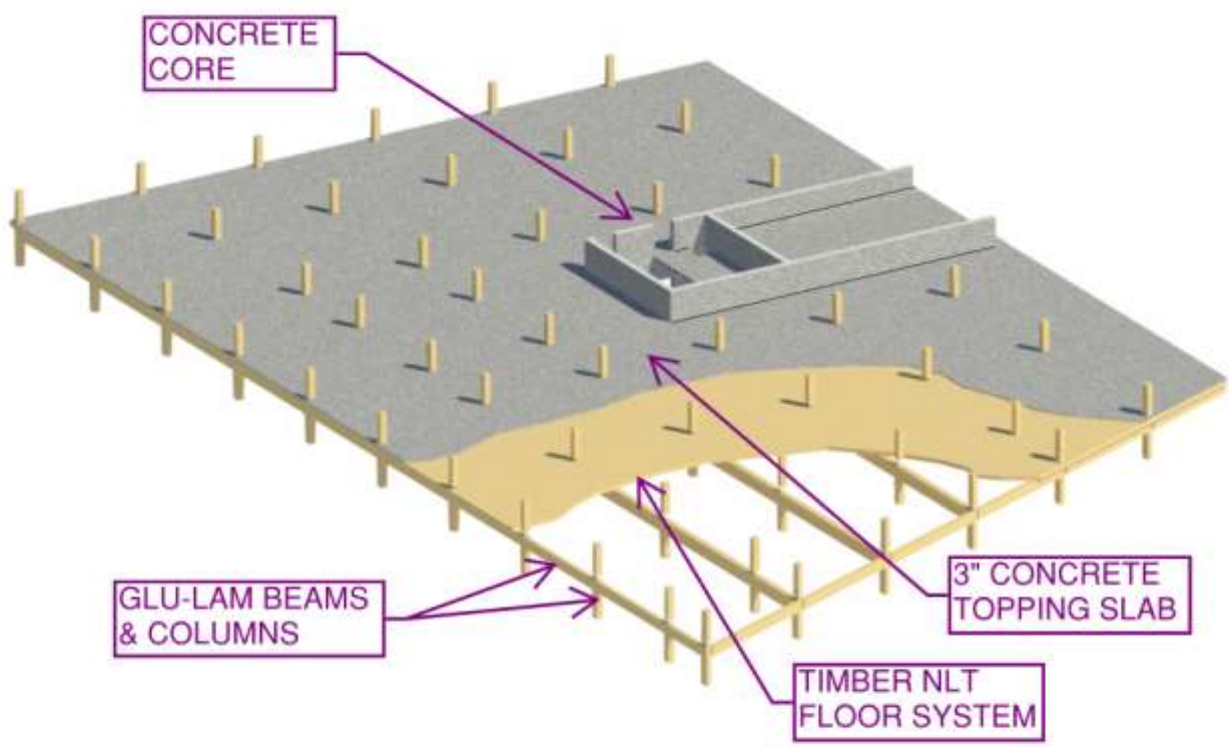

Figure 2: Portion of Floor Plate - Design A

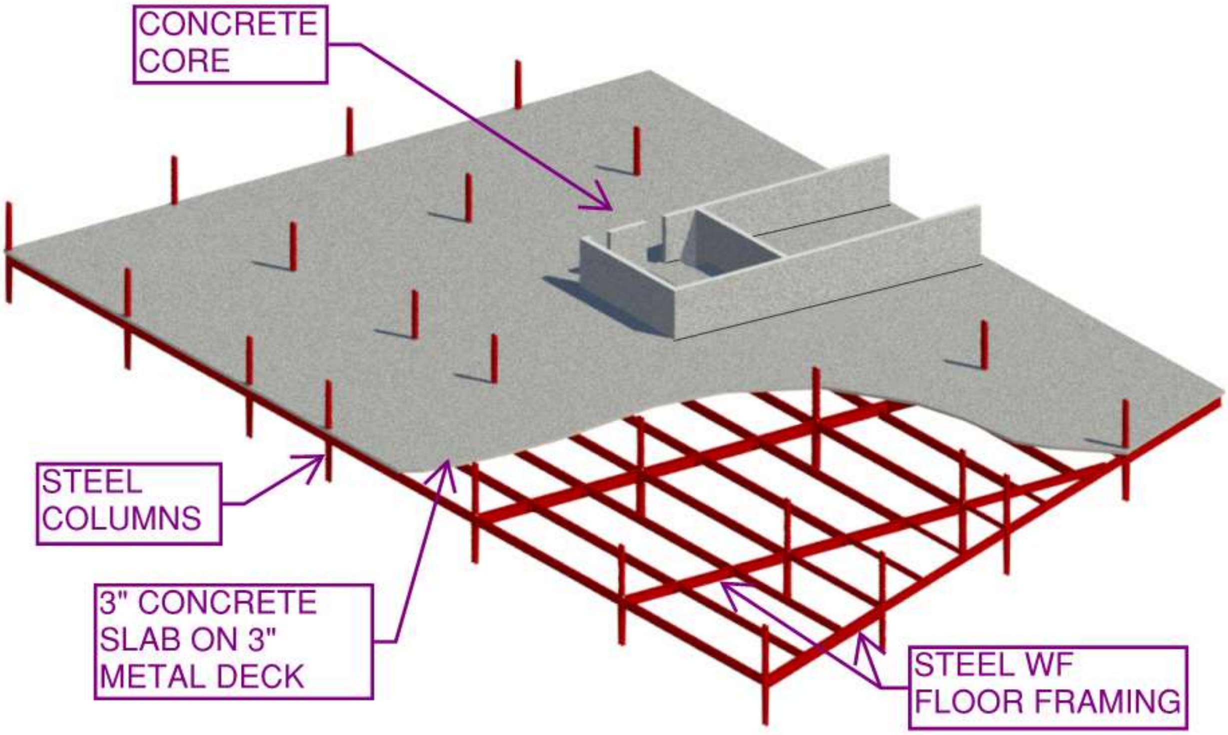

Figure 3: Portion of Floor Plate - Design B

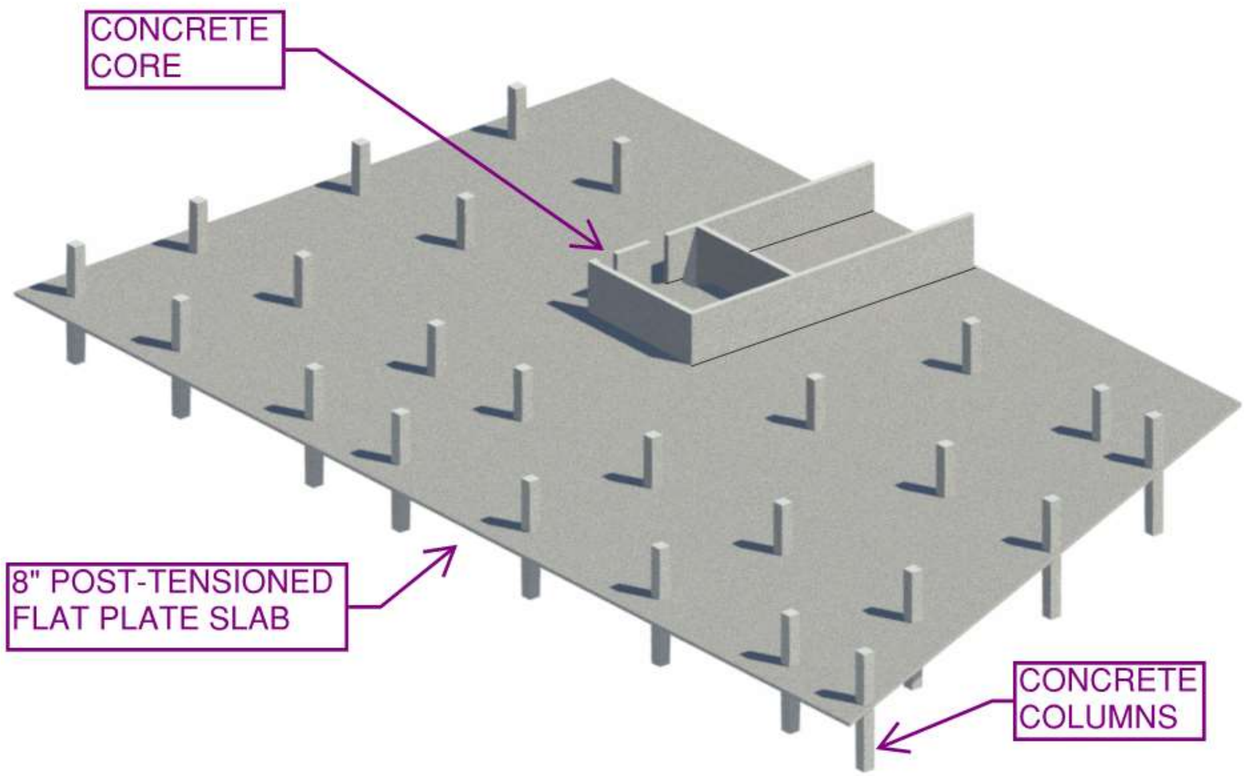

Figure 4. Portion of Floor Plate - Design C

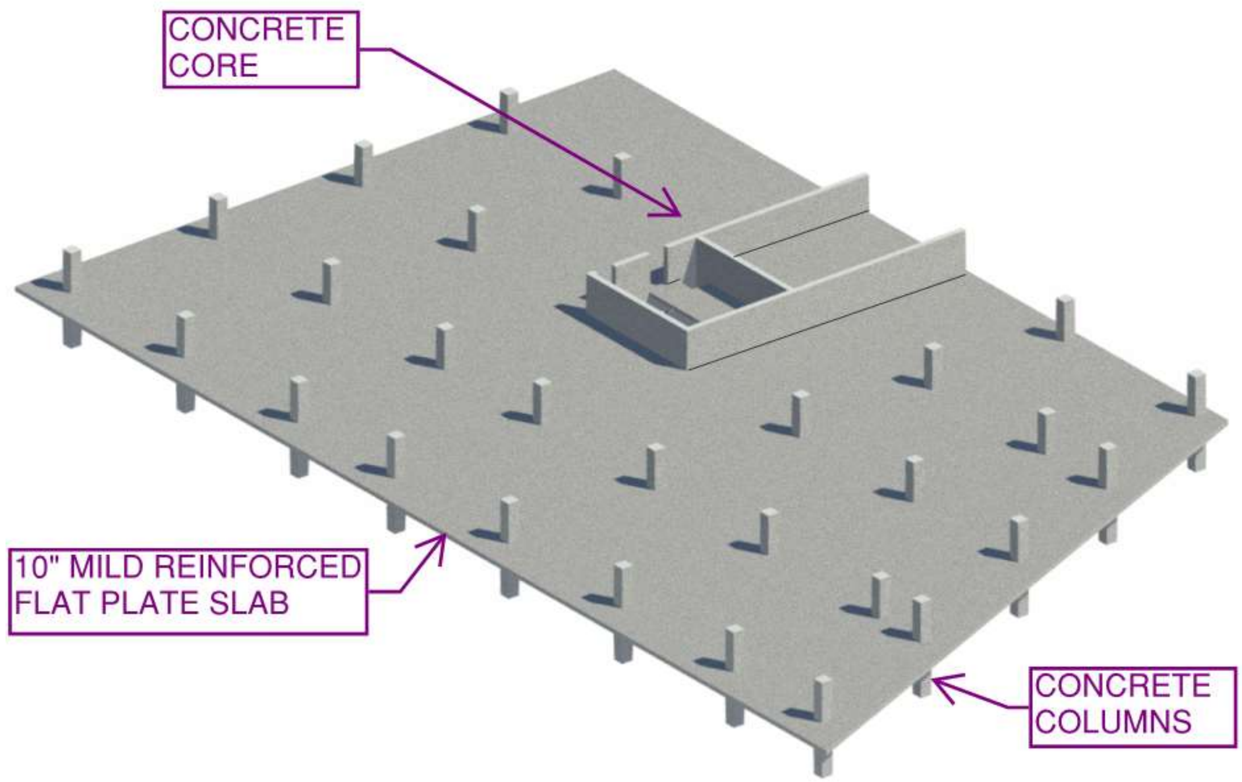

Figure 5. Portion of Floor Plate - Design D

Tally Results and Observations

The following figures show the results of the Tally LCA studies for both Cradle to Gate and Cradle to Grave boundary conditions.

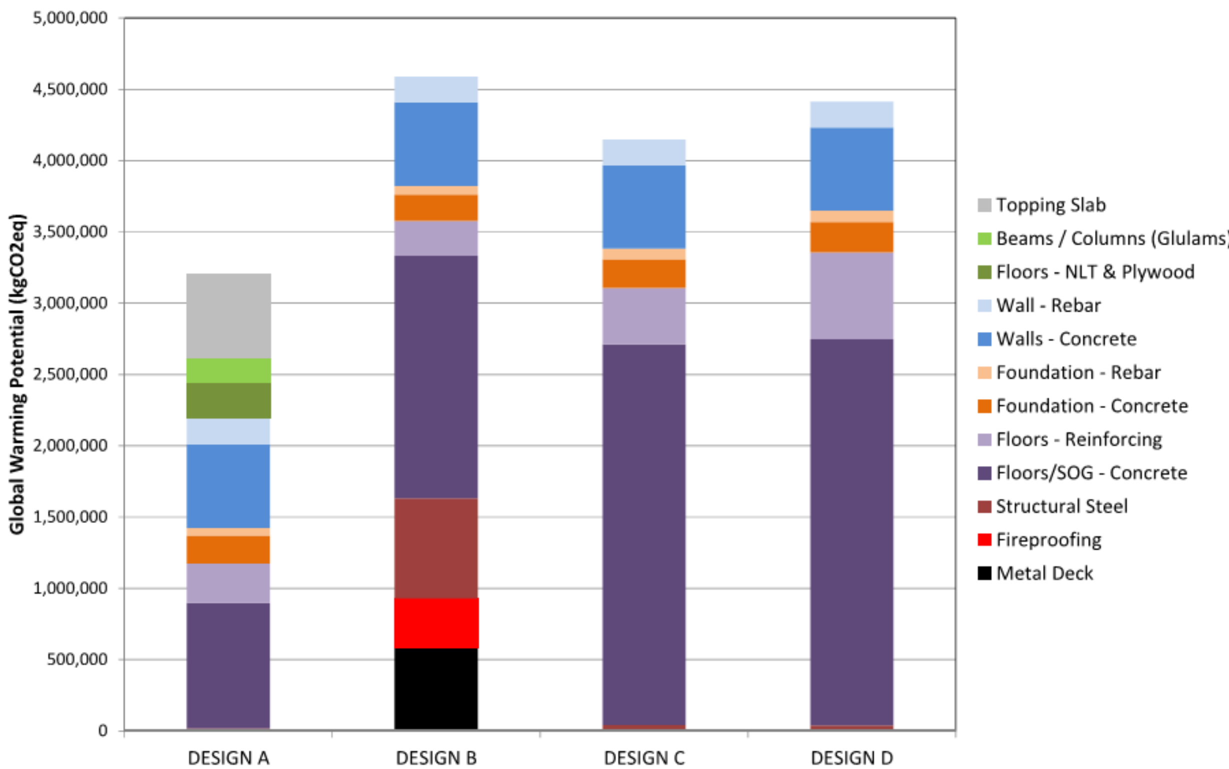

Figure 6. Tally Results - Cradle to Gate

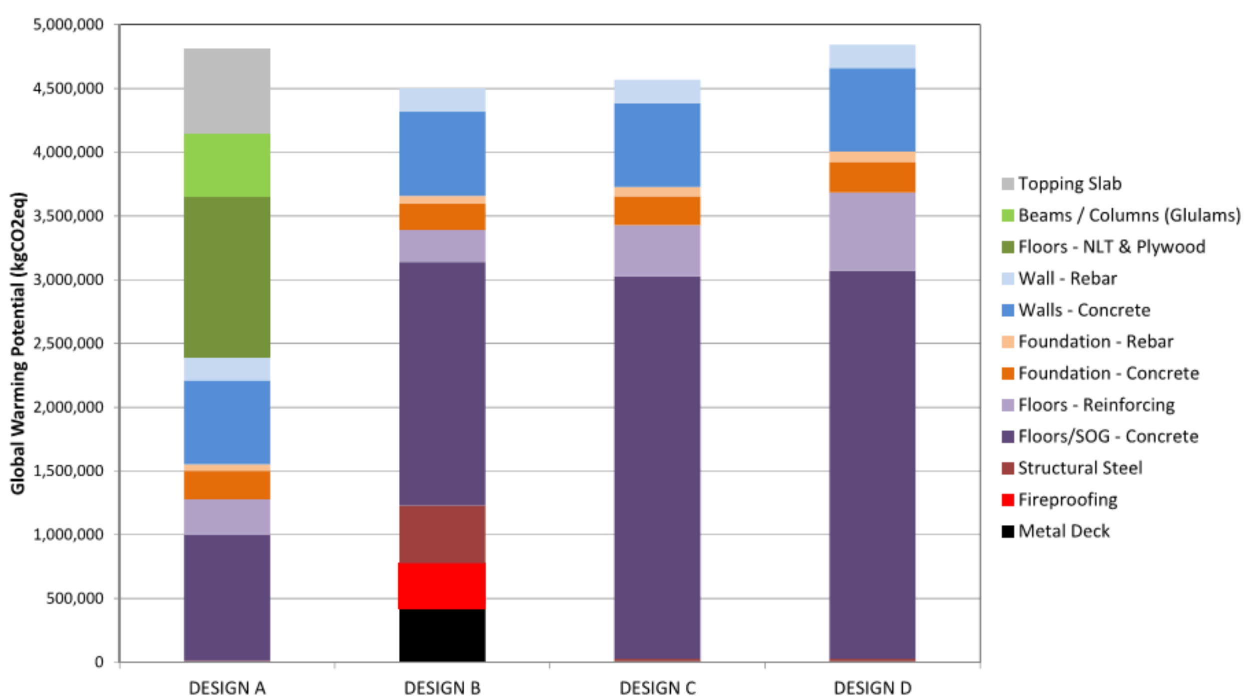

Figure 7. Tally Results - Cradle to Grave

In reviewing these findings, the cleanest data set comparison is between Design C (PT slab system) and Design D (mild reinforced slab system), as both structural systems are governed by the same PCR's. The LCA results of this study, with its noted qualifications and industry average concrete mix data, indicate the PT slab system (Design C) has approximately 5% less GWP than the mild slab system (Design D). PT slabs can achieve the same spans with reduced thickness, thus resulting in less concrete volume. However, due to high early strength requirements of PT slabs, the benefits of lower overall concrete quantities are partially offset by the use of mixes with higher cement requirements. As a result, unless time to PT stressing is adjusted from current industry practice, the largest improvement between the respective GWPs between Designs C and D is the lower reinforcement quantities within the PT slabs.

When comparing designs in the Cradle to Gate scope, the composite steel slab scheme (Design B) exhibits a lower GWP than the mild concrete slab scheme (Design D), and similar GWP to the concrete PT slab scheme (Design C). It is worth noting that while spray-applied fireproofing for the steel framing is included in this study, the added GWP associated with architecturally finishing around steel columns and added dropped ceilings is not included. These components tend to be more prevalent in steel buildings than concrete and heavy timber buildings that frequently leave columns and slab soffits exposed. Another issue outside the scope of this study is that many mild and PT slab systems allow for MEP system routing directly under the slab in lieu of below or through beam framing, allowing floor to floors to often be one to two feet shorter when compared to steel or wood system alternatives. Larger floor-to-floor dimensions create greater cladding surface area and interior partition wall heights, which can impact the overall project GWP. These secondary systems were not considered as part of this study, but should be for any whole building LCA efforts that extend beyond the structural frame.

Perhaps most interesting to note is that based upon the embodied carbon datasets used by Tally, the timber floor scheme (Design A) contains a higher global warming potential than might have been anticipated, especially when compared with the steel system in the Cradle to Grave study. This can be attributed to two significant factors. First is the significant increase in GWP for the timber components when factoring in the end of life phase.

The timber PCR assumes that the wood components will decompose or be incinerated at end of life. This issue is discussed in greater length in subsequent pages.

Another unique aspect contributing to the GWP of the heavy timber building is that a 3-inch concrete topping was required for comparable vibration and acoustic performance to the other systems, in order to meet Class-A office standards. If the mass timber building design included different alternatives for vibration and acoustical control, there may be a way to decrease in the overall global warming potential for the mass timber design, provided the concrete topping could be reduced or eliminated. However, it is common that manly architects and building owners do not want to hide the mass timber structure frame for aesthetic reasons; therefore this paper assumes the concrete topping slab as a more accurate representation of the timber solution as it would be designed and constructed.

Figure 8 was derived from the LCA results and illustrates Tally's assumption of the percent of embodied carbon, for the most common materials found in the four building designs, attributed to each life cycle relative to the total Cradle to Grave GWP. Note that the summation of "Manufacturing (Cradle to Gate)" and "End of Life" phases represent 100% of the total Cradle to Grave environmental impact.

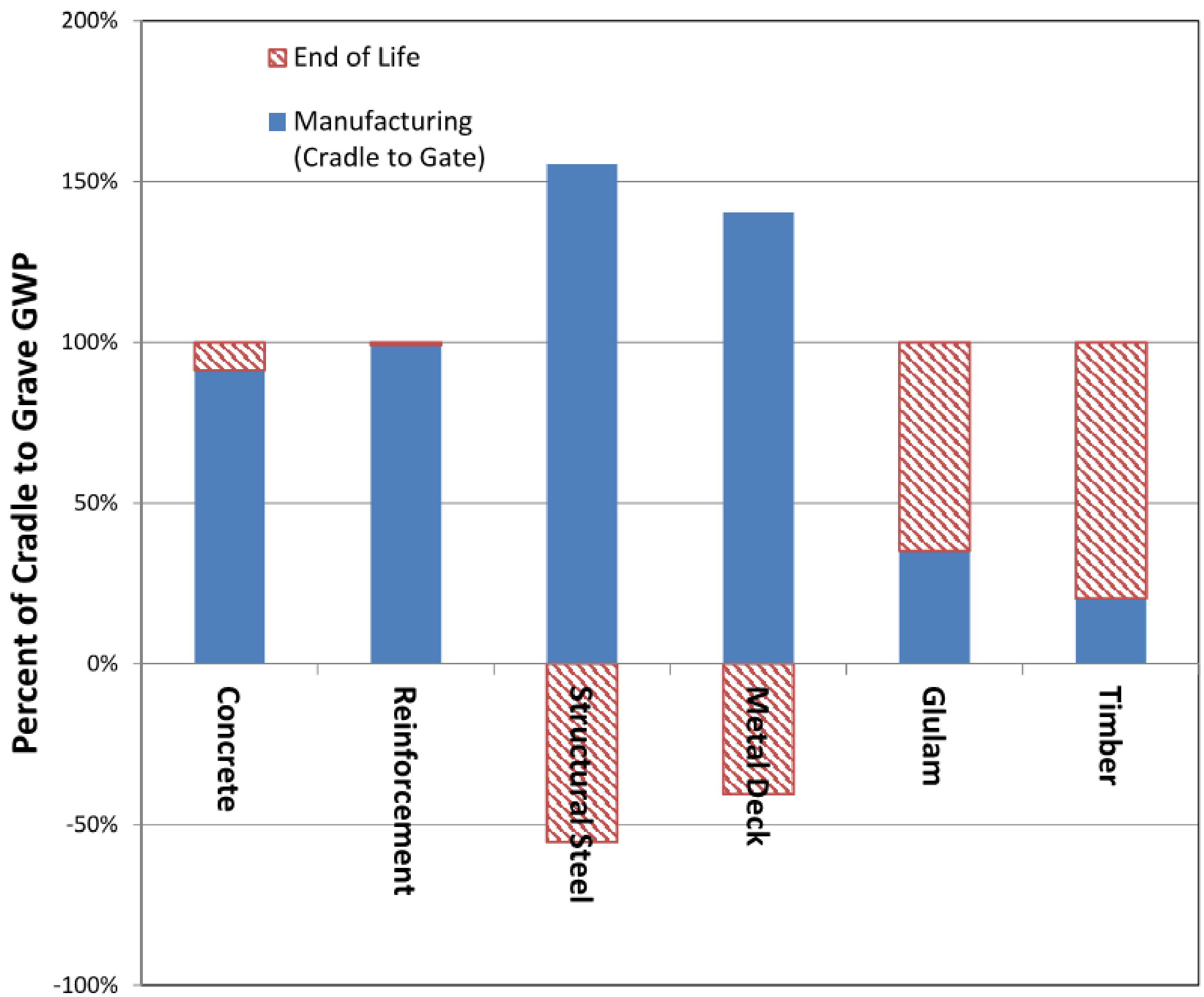

Figure 8. Sources of Global Warming Potential by Material in Life Cycle Scope of Cradle to Grave

Unlike building components such as interior finishes and MEP equipment, which are more prone to updating and replacing, the primary structure(barring low recurrence, high-impact events such as earthquakes, hurricanes, or fires), sees little in the form of maintenance, repair and replacement over a 60 year building life. For this reason, life cycle stages B2-B4, while included in the Cradle to Grave study, result in a negligible delta when comparing Cradle to Gate with Cradle to Grave. The end of life phases C2-C4 and D by contrast, can result in a significant delta between Cradle to Gate and Cradle to Grave boundary conditions. Due to inconsistencies in the varying materials PCR's, the magnitude and even the sign of this delta can vary between the materials of steel, concrete and timber.

The global warming potential of wood (glulam and softwood timber) and steel (structural steel and metal deck) are both highly dependent on the scope of the LCA, with inconsistencies and in some conditions unique industry slanted data sets coming from the PCR's and their resulting EPD's of both materials. When considering a Cradle to Gate scope within Tally, wood has a very low GWP relative to concrete and steel structures, but the North American wood database referenced by Tally does not consider FSC certified wood as the referenced EPDs are industry averages, and specifically ignores land impact issues associated with the harvesting of the materials, such as road building and site disruption, or lost forest carbon sequestration by the trees not continuing to grow on the site. The database for wood also assumes that at the end of the building life the timber is not reused and the carbon sequestered in the wood is eventually released into the atmosphere (e.g. through burning or decaying), which is the reason for the significant increase in GWP in the mass timber structure in the end of use phase.

LCA studies by others (for example see Mahler and Schneider 2016) have also shown considerable data scatter on how embodied carbon footprints for timber should be accounted for. LCA data sets other than Tally sometimes report timber as a negative carbon footprint when consumed in a project. The conclusion of Mahler and Schneider is that the databases account for CO2 using different methods (Mahler and Schneider 2016). The differences led to "[surprising results] and deviations of this order of magnitude were not expected" (Mahler and Schneider 2016). Despite these differences, one cannot today conclude that the quality of one database exceeds that of another, from a data comparison perspective. This is an area in need of further independent research for how to accurately handle timber LCA findings.

Conversely, when compared with the timber PCR, the PCR for rolled structural steel provides a negative end of life global warming potential, which the U.S. industry argues is indicative of the high rates of recycled steel content that goes into these specific steel building products. Tally uses a database containing a mixture of domestic and international steel, so it is difficult to quantify how much of the steel is recycled and how much is virgin. This partially picks up on the difference in energy consumed when steel comes from virgin ore feed stocks, or from recycled products that are re-melted and used again, and highlights the value of using higher recycled material contents in the steel. This is a relevant point for industry average LCA data for steel, but it should be specifically understood what production processes are used in the making of the steel product for more detailed LCA investigations. One finding is that the majority of sheet and plate steel (metal decking and metal studs being one example), where dimensional tolerances are more exacting, typically comes from virgin iron ore feed stock and a blast furnace at the mill. Rebar and rolled beam shapes more frequently come from a largely recycled material feed stock and an electric arc furnace at the mill. The carbon footprints between these two mill processes is too significant to ignore, but is currently not reported separately by industry.

For this paper, we have not attempted to debate the validity of the above assumptions by these industries; we have simply reported and used what is currently stated within their PCR’s and EPD’s for industry average information, as reported within Tally. For long-term credibility, these noted areas need future validation, most likely from independent third parties and not the institutions with conflicts of interest who are promoting their particular material.

It is important to maintain consistency between PCR scopes when making LCA comparisons, but what happens if the results of Cradle to Gate are compared to Cradle to Grave? Figure 10 shows the global warming potential in kilograms of carbon dioxide equivalent per square meter for the various schemes. The Cradle to Gate and Cradle to Grave results are reported as well as the relative difference of these two values. The relative magnitude of this difference is partly the result of the differing assumptions made in the respective materials’ PCRs.

The range shown in Figure 9 and the above discussions illustrate that making a decision on a sustainability “winner” between the different alternative building systems with today’s available LCA information is not appropriate. There are inherent assumptions and approximations that could change the results even within a given life cycle boundary.

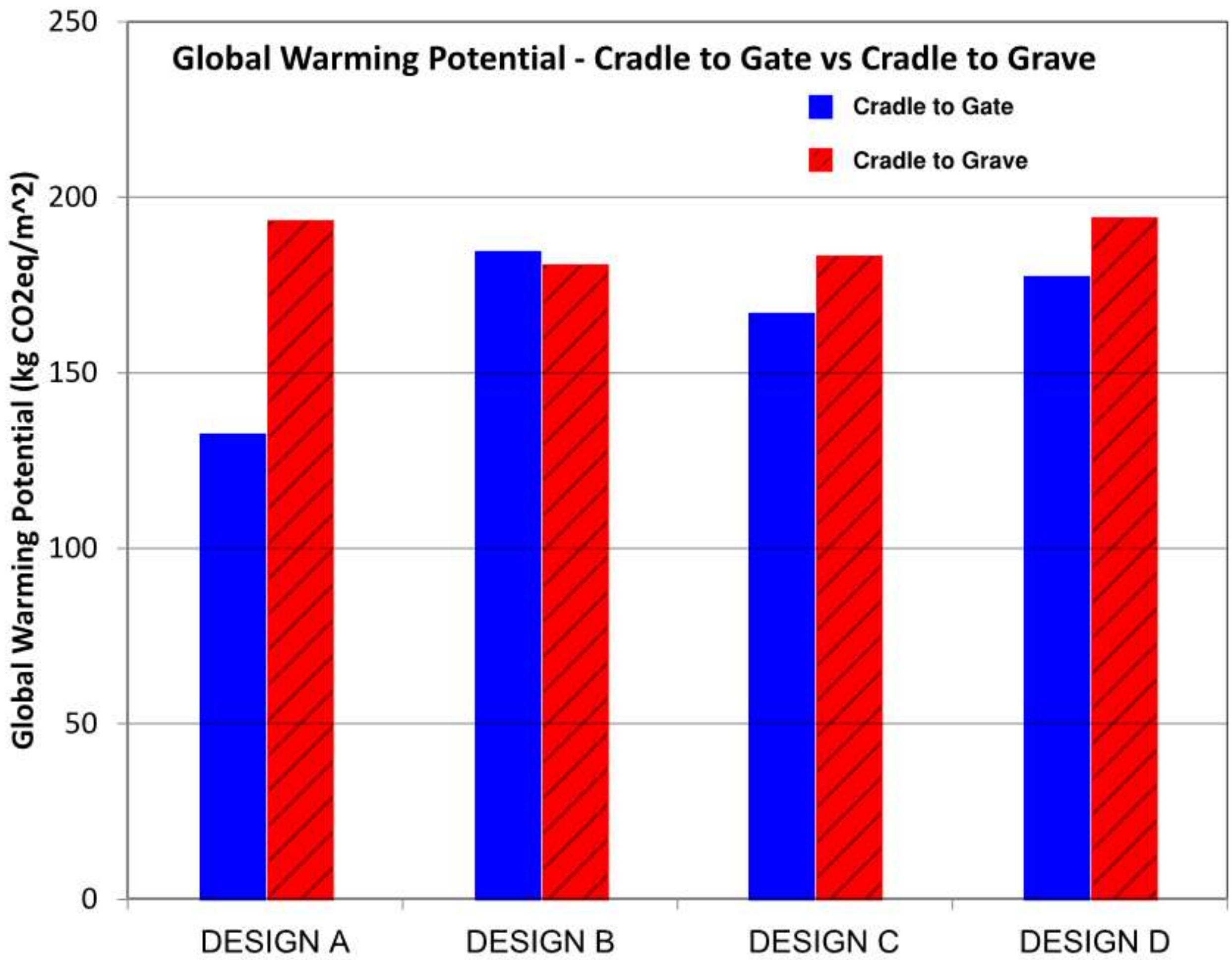

Figure 9. Case Study Results – Relative Difference in Global Warming Potential for Cradle to Gate vs Grave

Limitations of This Study

Dataset Limitations and Findings

As previously explained, with today's data it is difficult to compare the GWP of timber, concrete, and steel because of the differences in EPDs and PCRs developed by the material industries. Differences in the applicable PCRs for each material are some of the cause of the differences in the GWP of the "End of Life" between timber, concrete, and steel.

While GaBi was one of the data sets used in the previously discussed Mahler and Schneider study and all datasets showed a similar “lowest carbon” solution regardless of the database considered, variations on how wood is considered within the LCA industry varies widely. The source of much of this variation comes from how timber is handled, including ignoring upstream impacts within their PCR boundary conditions and the handling of negative carbon credits due to the use of a bio based material.

It is common in the LCA community to disregard any attempt at comparing the embodied carbon between materials, taking the stance that LCA studies should only compare variations within the same material. For data sets as they exist today and from findings presented in this paper, this would seem to be appropriate. It would be useful to address this topic within building industry PCRs for the further advancement of the science of Life Cycle Analysis.

Software and Database Limitations

Results of this study are limited by the selection of Tally’s industry averaged data sets, which are based upon the GaBi database, along with the quality of the Revit model detail provided for the study. While this Tally-based study is based upon design findings and not as-built findings, this is consistent with what can be achieved today with early design LCA efforts. More exacting LCA’s by the research community can and should be accomplished around limitations noted within this study, to allow such future efforts to occur with greater confidence and surety.

Parameter Limitations

Several limitations resulted from the parameter selection for the building. The low seismicity location of the building site indicates that the demands and lateral resisting system did not significantly differ from design to design.

In addition, the building height is the same for these comparisons despite the fact that the structural depths differ. The impact to the overall building height was therefore not considered.

Structural Design Limitations

The seismic and wind hazards of a project site also impacts the relevance of this study, as different sites yield different load demands, which would thus result in different structural proportioning. This case study project was not located in a high seismic zone, with the lateral design being controlled by wind. If this building were situated on a seismically active site on the West Coast of the United States, the lateral system and foundations would be likely to be controlled by seismic forces which will penalize buildings with a higher mass more. Note that the Design A (mass timber floor), and Design B (composite structural steel) have comparable floor system weights, and are much lighter than the concrete designs. The floor diaphragm of Design A, though, would likely require more reinforcement, to meet the lateral system requirements of high seismic loading. The floor diaphragms of Designs B, C, and D would externally look the same in wind or high seismic locations, but the internal rebar to each system would increase. A future effort will be to run this study again, but based upon a high-seismic location to directly quantify those impacts.

Conclusions

Given these limitations, this paper does not show that a decisive GWP winner can be chosen between the four different building frame options studied, based upon a material system choice alone and the data sets considered for this study. This was not the anticipated conclusion at the start of this investigation, but we look forward to future efforts which help clarify the shortcomings and inconsistencies of LCA data sets. This paper affirms that designers should choose materials that are most materially efficient for the intended building use, and then optimize and economize the design to save on quantities while also finding ways to decrease the embodied carbon of that material choice.

Moving forward, it is important that efforts work to better align the data from the PCR's and EPDs between timber, concrete, and steel, especially in how each looks at the Cradle to Gate and Cradle to Grave approaches of their data set boundaries. It is also critical to attain material sourcing data specific to the manufacturing stage in order to attain meaningful embodied carbon footprint information. For structural steel and reinforcing steel, this needs to include mill specific information; for concrete, this needs to include plant production information; and for timber, this needs to include impacts associated with the logging process such as building roads, and sequestered carbon losses had the trees remained growing or whether the forest is sustainably managed.

The results of this study should not be taken as hard evidence of the “carbon winner” between concrete, timber, and steel whole building systems. From the LCA information considered from this study, such conclusions were not possible to make. Instead, it should be seen as a comparative look at where we are today with at least one thoughtful LCA tool that is available to the design community, and where the limitations are that need to continue to be worked on. Tally and similarly related software provide a major step forward in being able to systematically quantify within the design process the baseline of a building’s embodied carbon footprint, and to begin to quantify the sustainable value of design optimization and the use of fewer materials. This allows for identifying trends in embodied carbon impacts between various building system combinations to be explored, and helps designers and owners make more informed decisions. The Life Cycle Analysis system and PCR and EPD processes in place today in the US, though do not yet give statistically compatible data for directly comparing the embodied carbon footprint of one material type against another, and claims made today to the contrary should be very critically evaluated before believing them to be true.

Appendix A: Material Quantity Tables For Four Design Schemes

Table 1A – 1D: Quantities Based on Element Tributary Area

Table 1A: Design A – NLT Floor System

				STEEL QUANTITIES NORMALIZED BY TRIBUTARY FLOOR AREA / VOLUME	
		Area / Volume Quantities		Average Quantities [(Rebar, PT, Steel Tonnage) ÷ (Trib Floor Area or Volume)]	
		Floor Area	Volume		
	Material Properties	(ft^2)	(ft^3 wood, yd^3 concrete)	(lb/ft^2)	(lb/yd^3)
Glulam Columns, Spruce-Pine-Fir	f'b = 2,400 PSI	--	7,981	--	--
Glulam Beam, Spruce-Pine-Fir	f'b = 2,400 PSI	--	22,900	--	--
Floors - NLT & Plywood, Spruce-Pine-Fir	f'b = 2,400 PSI	--	120,600	--	--
Miscellaneous Steel	Fy = 46 KSI	279,532	--	0.02	--
Metal Deck	Fy = 50 KSI	2,166	--	2.3	--
Concrete Basement Walls	f'c = 4 KSI	--	380	--	150
Concrete Shear Walls	f'c = 5 KSI	--	1,368	--	180
Concrete Columns	f'c = 5 KSI	--	166	--	190
Topping Slab	f'c = 4 KSI	178,440	--	0.7	--
Slab on Grade	f'c = 4 KSI	29,740	--	2	--
Concrete Slabs (mild reinforced)	f'c = 5 KSI	69,186	--	4	--
Mat Foundation	f'c = 4 KSI	--	8,942	--	160
Spread Footings	f'c = 4 KSI	--	13,578	--	80
	Gross Project Floor Area	279,532			

Table 1A: Design B – Steel Framing and Slab on Metal Deck Floor System

				STEEL QUANTITIES NORMALIZED BY TRIBUTARY FLOOR AREA	
		Total Quantities		Average Quantities [(Rebar, PT, Steel Tonnage) ÷ (Floor Area or Volume)]	
		Floor Area	Volume		
	Material Properties	(ft^2)	(yd^3)	(lb/ft^2)	(lb/yd^3)
Steel Beams and Columns	Fy = 50 KSI	180,606	--	12	--
Miscellaneous Steel	Fy = 46 KSI	279,532	--	0.02	--
Steel Spray Applied Fireproofing	--	--	638	--	15
Metal Deck (Roof + Composite Deck)	Fy = 50 KSI	180,606	--	2.3	--
Concrete Basement Walls	f'c = 4 KSI	--	380	--	150
Concrete Shear Walls	f'c = 5 KSI	--	1,368	--	180
Concrete Columns	f'c = 5 KSI	--	166	--	190
Concrete (slab on metal deck)	f'c = 4 KSI	178,440	--	1	--
Slab on Grade	f'c = 4 KSI	29,740	--	2	--
Concrete Slabs (mild reinforced)	f'c = 5 KSI	69,186	--	4	--
Mat Foundation	f'c = 4 KSI	--	8,942	--	160
Spread Footings	f'c = 4 KSI	--	13,578	--	90
	Gross Project Floor Area	279,532			

Table 1A: Design C – Post-Tensioned Slab Floor System

		Total Quantities		STEEL QUANTITIES NORMALIZED BY TRIBUTARY FLOOR AREA	
				Average Quantities [(Rebar, PT, Steel Tonnage) ÷ (Floor Area or Volume)]	
	Material Properties	Floor Area (ft^2)	Volume (yd^3)	(lb/ft^2)	(lb/yd^3)
Miscellaneous Steel	**Fy = 46 KSI**	279,532	--	0.02	--
Metal Roof Deck	**Fy = 50 KSI**	2,166	--	2.3	--
Concrete Basement Walls	**f'c = 4 KSI**	--	380	--	150
Concrete Shear Walls	**f'c = 5 KSI**	--	1,368	--	180
Concrete Columns	**f'c = 5 KSI**	--	636	--	190
Slab on Grade	**f'c = 4 KSI**	29,740	--	2	--
Post-Tensioned Concrete Slabs	**f'c = 5 KSI**	208,180	--	2.5 (Rebar), 0.9 (PT)	--
Mild Reinforced Concrete Slabs	**f'c = 5 KSI**	39,446	--	4	--
Mat Foundation	**f'c = 4 KSI**	--	8,942	--	170
Spread Footings	**f'c = 4 KSI**	--	13,578	--	100
	Gross Project Floor Area	279,532			

Table 1A: Design D – Mild Slab Floor System

		Total Quantities		STEEL QUANTITIES NORMALIZED BY TRIBUTARY FLOOR AREA	
				Average Quantities [(Rebar, PT, Steel Tonnage) ÷ (Floor Area or Volume)]	
	Material Properties	Floor Area (ft^2)	Volume (yd^3)	(lb/ft^2)	(lb/yd^3)
Miscellaneous Steel	**Fy = 46 KSI**	279,532	--	0.02	--
Metal Roof Deck	**Fy = 50 KSI**	2,166	--	2.3	--
Concrete Basement Walls	**f'c = 4 KSI**	--	380	--	150
Concrete Shear Walls	**f'c = 5 KSI**	--	1,368	--	180
Concrete Columns	**f'c = 5 KSI**	--	636	--	190
Slab on Grade	**f'c = 4 KSI**	29,740	--	2	--
Mild Reinforced Concrete Slabs	**f'c = 5 KSI**	247,626	--	4	--
Mat Foundation	**f'c = 4 KSI**	--	8,942	--	180
Spread Footings	**f'c = 4 KSI**	--	16,293	--	110
	Gross Project Floor Area	279,532			

Table 2A – 2D: Quantities Based on Gross Project Floor Area (279,532 ft^2)

Table 2A: Design A – NLT Floor System

		STEEL QUANTITIES NORMALIZED BY GROSS PROJECT FLOOR AREA	CONCRETE & TIMBER QUANTITIES NORMALIZED BY GROSS PROJECT FLOOR AREA
		Average Quantities [(Rebar, PT, Steel Tonnage) ÷ (Gross Proj. Floor Area or Volume)]	**Average Quantities [(Concrete or Wood Volume) ÷ (Gross Proj. Floor Area)]**
	Material Properties	**(lb/ft^2)**	**(ft^3/ft^2)**
Glulam Columns, Spruce-Pine-Fir	**f'b = 2,400 PSI**	--	0.029
Glulam Beam, Spruce-Pine-Fir	**f'b = 2,400 PSI**	--	0.082
Floors - NLT & Plywood, Spruce-Pine-Fir	**f'b = 2,400 PSI**	--	0.431
Miscellaneous Steel	**Fy = 46 KSI**	0.02	--
Metal Deck	**Fy = 50 KSI**	0.02	--
Concrete Basement Walls	**f'c = 4 KSI**	--	0.037
Concrete Shear Walls	**f'c = 5 KSI**	--	0.132
Concrete Columns	**f'c = 5 KSI**	--	0.016
Topping Slab	**f'c = 4 KSI**	--	0.160
Slab on Grade	**f'c = 4 KSI**	--	0.035
Concrete Slabs (mild reinforced)	**f'c = 5 KSI**	--	0.206
Mat Foundation	**f'c = 4 KSI**	--	0.864
Spread Footings	**f'c = 4 KSI**	--	1.311

Table 2B: Design B – Steel Framing and Slab on Metal Deck Floor System

		STEEL QUANTITIES NORMALIZED BY GROSS PROJECT FLOOR AREA	CONCRETE / TIMBER QUANTITIES NORMALIZED BY GROSS PROJECT FLOOR AREA
		Average Quantities [(Rebar, PT, Steel Tonnage) ÷ (Gross Proj. Floor Area or Volume)]	**Average Quantities [(Concrete or Wood Volume) ÷ (Gross Proj. Floor Area)]**
	Material Properties	**(lb/ft^2)**	**(ft^3/ft^2)**
Steel Beams and Columns	**Fy = 50 KSI**	3.5	--
Miscellaneous Steel	**Fy = 46 KSI**	0.02	--
Steel Spray Applied Fireproofing	--	--	0.002
Metal Deck (Roof + Composite Deck)	**Fy = 50 KSI**	1.9	--
Concrete Basement Walls	**f'c = 4 KSI**	--	0.037
Concrete Shear Walls	**f'c = 5 KSI**	--	0.132
Concrete Columns	**f'c = 5 KSI**	--	0.016
Concrete (slab on metal deck)	**f'c = 4 KSI**	--	0.040
Slab on Grade	**f'c = 4 KSI**	--	0.035
Concrete Slabs (mild reinforced)	**f'c = 5 KSI**	--	0.206
Mat Foundation	**f'c = 4 KSI**	--	0.864
Spread Footings	**f'c = 4 KSI**	--	1.311

Table 2C: Design C – Post-Tensioned Slab Floor System

	Material Properties	STEEL QUANTITIES NORMALIZED BY GROSS PROJECT FLOOR AREA	CONCRETE / TIMBER QUANTITIES NORMALIZED BY GROSS PROJECT FLOOR AREA
		Average Quantities [(Rebar, PT, Steel Tonnage) ÷ (Gross Proj. Floor Area or Volume)]	Average Quantities [(Concrete or Wood Volume) ÷ (Gross Proj. Floor Area)]
		(lb/ft^2)	(ft^3/ft^2)
Miscellaneous Steel	**Fy = 46 KSI**	0.02	--
Metal Roof Deck	**Fy = 50 KSI**	0.02	--
Concrete Basement Walls	**f'c = 4 KSI**	--	0.037
Concrete Shear Walls	**f'c = 5 KSI**	--	0.132
Concrete Columns	**f'c = 5 KSI**	--	0.061
Slab on Grade	**f'c = 4 KSI**	--	0.035
Post-Tensioned Concrete Slabs	**f'c = 5 KSI**	--	0.496
Mild Reinforced Concrete Slabs	**f'c = 5 KSI**	--	0.118
Mat Foundation	**f'c = 4 KSI**	--	0.864
Spread Footings	**f'c = 4 KSI**	--	1.311

Table 2D: Design D – Mild Slab Floor System

	Material Properties	STEEL QUANTITIES NORMALIZED BY GROSS PROJECT FLOOR AREA	CONCRETE / TIMBER QUANTITIES NORMALIZED BY GROSS PROJECT FLOOR AREA
		Average Quantities [(Rebar, PT, Steel Tonnage) ÷ (Gross Proj. Floor Area or Volume)]	Average Quantities [(Concrete or Wood Volume) ÷ (Gross Proj. Floor Area)]
		(lb/ft^2)	(ft^3/ft^2)
Miscellaneous Steel	**Fy = 46 KSI**	0.02	--
Metal Roof Deck	**Fy = 50 KSI**	0.02	--
Concrete Basement Walls	**f'c = 4 KSI**	--	0.037
Concrete Shear Walls	**f'c = 5 KSI**	--	0.132
Concrete Columns	**f'c = 5 KSI**	--	0.061
Slab on Grade	**f'c = 4 KSI**	--	0.035
Mild Reinforced Concrete Slabs	**f'c = 5 KSI**	--	0.738
Mat Foundation	**f'c = 4 KSI**	--	0.864
Spread Footings	**f'c = 4 KSI**	--	1.574

References

ASTM Standard E2921. 2016, “Standard Practice for Minimum Criteria for Comparing Whole Building Life Cycle Assessments for Use with Building Codes, Standards, and Rating Systems,“ ASTM International, West Conshohocken, PA, 2016, DOI: 10.1520/E2921-16A. www.astm.org

Athena Sustainable Materials Institute. 2016. "LCA LCI LCIA LCC: What’s the Difference?" Web. http://www.athenasmi.org/resources/about-lca/whats-the-difference/

Boyd, G. and Zhang, G. 2011. Measuring Improvement in the Energy Performance of the U.S. Cement Industry, Duke University Department of Economics.

Carbon Leadership Forum. 2015. EPDs and PCRs. Web. http://carbonleadershipforum.org/epds-and-pcrs.html

Carma. Carma. 2016. Web. http://www.carma.org/

Clark, D. 2013. “Information paper – 12: Embodied carbon case studies for office buildings.” Web. http://www.wholecarbonfootprint.com/

Davies, D. and Klemencic, R. 2014. “Life Cycle Analysis: Are We There Yet?” *Future Cities: Towards Sustainable Vertical Urbanism: A collection of state-of-the-art, multi-disciplinary papers on tall buildings and sustainable cities.* Proceedings of the CTBUH 2015 Shanghai Conference, China, 16-19 September 2014. Council on Tall Buildings and Urban Habitat: Chicago.

Farrelly, D. 1984*. The Book of Bamboo. San Francisco: Sierra Club Books.*

FPInnovations. 2011. Product Category Rules (PCR) For preparing an Environmental Product Declaration (EPD) For North American Structural and Architectural Wood Products Version 1. Accessed via Web. https://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Pages/default.aspx

FPInnovations. 2015. Product Category Rules (PCR) For preparing an Environmental Product Declaration (EPD) For North American Structural and Architectural Wood Products Version 2. Accessed via Web. https://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Pages/default.aspx

Harmon, M.E., Moreno, A., and Domingo, J.B. 2009. Effects of Partial Harvest on the Carbon Stores in Douglas fir/Western Hemlock Forests: A Simulation Study. *Ecosystems* 12:777-791.

Hudiburg, T.W., S. Luyssaert, P. Thornton, B.E. Law. 2013. Interactive effects of environmental change and management strategies on regional forest carbon emissions. *Environmental Science & Technology* 47:13132-40

KT Innovations, *Tally®* (Version 2017.06.15.01, 6/18/2017), Philadelphia, PA: KT Innovations, 2017

Mahler, P., Schneider, P. 2016. The influence of databases on the Life Cycle Assessment (LCA) of building components – A comparison of databases using three different wall constructions. *Life-Cycle of Engineeirng Systems: Emphasis on Sustainable Civil Infrastructure – Bakker, Frangopol & van Breugel*. pp 967-974.

Natural Capital Partners. 2016. Natural Capital Partners. Web. http://www.naturalcapitalpartners.com/

Nisqually Land Trust. 2016. Nisqually Land Trust. Web. http://nisquallylandtrust.org/

Skone, T.J. 2013. LCA at the Department of Energy (DOE), National Energy Technology Laboratory (NETL). Presentation accessed via Web. http://lcacenter.org/lcaxiii/final-presentations/964.pdf

U.S. Green Building Council. 2013. Materials and Resources Credit: Building Life-Cycle Impact Reduction. *LEED Reference Guide for Building Design and Construction.*