Differences in Embodied Carbon Assessments of Structural Systems

Megan Stringer, PE, LEED AP BD+C
Chair, SEAONC SDC
Holmes Culley
San Francisco, CA

Matthew Comber, SE, LEED AP BD+C
Vice Chair, SEAONC SDC
Project Frog
San Francisco, CA

Abstract

As operational carbon emissions associated with buildings decrease due to improvements in mechanical systems and passive design strategies, the embodied carbon of a structure emerges as a significant contributor to the carbon expenditure over the building's life-cycle. Life-Cycle Assessment (LCA) of embodied carbon in structures is thus increasingly utilized in structural engineering projects of various scales to aid designer, owner and contractor decisions. As the tools used by structural engineers can differ, this study seeks to understand the differences in embodied carbon results offered by various published LCA methodologies.

LCA allows for an accounting of the environmental impacts of a building across the manufacturing, transportation, and construction stages as well as operation and eventual demolition or reuse. It allows structural engineers to compare and contrast various structural system strategies and understand the impacts of decisions made in design. Performing an LCA is a complex undertaking as buildings include innumerable materials, are designed, manufactured and fabricated across multiple industries, and use highly variable construction practices. Despite these complexities LCA is a powerful methodology in offering an approximate measurement of environmental impacts for comparative purposes.

The Sustainable Design Committee (SDC) of SEAONC has built upon the work of the SEAOC SDC, which generated comparative LCAs of a 5-story office building using the Athena Impact Estimator (IE) and Kieran Timberlake's Tally to evaluate eight different structural systems. This committee's work considers SOM's Environmental Analysis Tool™ as alternate LCA methodology for comparison to the Athena Impact Estimator and Kieran Timberlake's Tally. This paper discusses the results from these tools and potential reasons for their variability for the reference of structural engineers considering their use on a project.

Acknowledgements

This paper is a result of the collaborative efforts of the SEAONC SDC. The co-chairs of the committee assembled this paper with the extensive help and co-authorship of Philip Bastiao, Devki Desai, Beth Grote, Erik Kneer, and Nicole Wang. Substantial support was also provided by the SEAOC SDC in providing background surrounding the Athena Impact Estimator and Kieran Timberlake Tally analyses and David Shook in educating the committee on the use and assumptions of the EA Tool™.

Introduction

Recent urbanization has initiated a substantial migration of humankind to cities. In response, construction in urban centers has grown in volume and speed. Infrastructure needs to be constructed or refurbished to meet the growing demands of today's urban populous. Particularly, the growth of urban centers in the state of California has further increased the role of the structural engineer in the sustainable design and construction process.

As the demand for denser cities spurs new construction of taller and larger buildings, the resulting increase in material usage has become noticeable. With construction material resources becoming more limited, the structural engineer can utilize tools such as LCA to quantify impacts and better understand how to conserve materials and other resources. The inventory of available LCA tools is growing, and it is important that engineers understand the differences between tools and how to best utilize them.

Although, for conventionally designed buildings, the environmental impact or embodied energy of the structure itself is still only a percentage of the impacts of building operations, this balance is shifting as HVAC and other building operation systems become more efficient. Thus, understanding, measuring, and reducing the amount of embodied energy in the structure will become increasingly important as our industry evolves. As the total energy used by a building is decreasing, the structural engineer is becoming responsible for an increasingly larger portion of the total building's environmental impact.

Performing an LCA is a complex undertaking as buildings include innumerable materials, are designed from multiple industries, and use highly variable construction practices. The foundation of an LCA is the data used in running the analysis. This life-cycle inventory (LCI) data includes all the individual energy and materials flows into and out of the environment for a particular product or process. There are both qualitative and quantitative methods for reporting this data and currently no consensus on the preferred collection method exists, creating a lack of consistency in data reporting. There are multiple LCI databases available to designers and each account for environmental impacts differently.

The SEAONC SDC has been further expanding upon the SEAOC SDC LCA study that investigated different structural systems and their relative environmental impacts with the Athena Impact Estimator for Buildings and Kieran Timberlake's Tally. This committee's study compares results from the Environmental Analysis Tool™ [SOM, 2013] to the relative impacts generated previously by the Athena Impact Estimator [Court et. al. 2013] and Kieran Timberlake's Tally [Court et. al. 20134. While each methodology accounts for overall environmental impact of a given design, each tool presents its own set of key features, assumptions, abilities and limitations. This paper explores these differences to aid the design professional in understanding how these tools can impact the design process.

SEAOC SDC Comparative LCA Study

The SEAOC SDC has been working on a comparative LCA study for the last 3 years. Initially the study considered the life-cycle impacts of eight different functionally equivalent versions of one building, using the Athena Impact Estimator LCA tool [Court et. al. 2013]. Later phases looked at Kieran Timberlake's LCA tool Tally [Court et. al. 2014].

The SEAOC study compared the five main LCA metrics of eight different functionally equivalent versions of one office building located in Los Angeles. Each iteration used the same floor plan, bay size, and design criteria, but considered different materials and structural systems:

- CS-1: Concrete Special Moment Frame
- CS-2: Concrete Shear Wall
- CS-3: Masonry Wall and Concrete Floor System
- CS-4: Masonry Wall and Steel Floor System
- CS-5: Steel Special Moment Frame
- CS-6: Steel Buckling Restrained Braced Frame
- CS-7: Light Timber with Buckling Restrained Braced Frame
- CS-8: Heavy Timber with Plywood Shear Walls
- CS-9: Light Timber with Plywood Shear Walls (note this building was studied by SEAOC after the publication of their study and was therefore not included in the original publication)

All eight buildings were designed to Schematic Design level, using basic computer modeling, proprietary design tables, and engineering judgment. The structure and foundation were the only building systems that were modeled in the LCA; other systems such as architectural, building envelope, etc. were not included in the study. It should be noted that use of the same plan layout for each of the systems likely resulted in inefficient designs for some of the structural systems considered, but it was determined to be a necessary approach in controlling variables across multiple structural systems. This also enabled necessary variable control as the tools were expanded in future phases of the study.

The SEAOC study initially utilized the LCA tool, the Athena IE version 4.02. The IE tool was chosen as it is the most widely used LCA program used for buildings in the U.S., can be downloaded for free, and be operated without advanced knowledge of LCA methods. Another feature of the IE is the ability to input a bill of materials directly into the program, via the Extra Basic Materials function. The IE also offers modules that estimate material quantities given certain building parameters, but the material quantities estimated by these modules typically did not match the quantities estimated independently through engineering the case study buildings, and often differed by more than a factor of two. Later phases of the study looked at the LCA results from updated versions of the IE tool and the LCA tool Tally.

From the SEAOC SDC LCA studies, the LCA results show that the wood buildings studied tended to have lower environmental impact than the steel buildings, which in turn had lower impacts than the concrete or masonry buildings.

Additionally, a positive correlation was found between the mass of the structure and its total environmental impact. Further phases of the SEAOC SDC LCA study are ongoing.

The Environmental Analysis Tool™

Skidmore, Owings & Merrill LLP has developed the Environmental Analysis Tool™ to address current sustainable design practices, quantify the embodied carbon dioxide equivalents incurred over the lifetime of a building, and include an approximation of the amount of those impacts that can be attributed to repairs of seismic damage. This cradle-to-grave life-cycle approach can allow designers, contractors, and owners to understand the implications of their projects early in the design process; quantify all the variables associated with embodied carbon dioxide during the construction phase; and measure the probable seismic damages in fiscal and carbon metrics during the service life of the building.

Carbon Mapping Early in Design

The environmental impact of a structure is proposed as an additional decision metric to consider in addition to other metrics such as available materials and constructability. All of these metrics must be considered at the earliest stages of design. To better inform the design team, carbon footprint assessments should be accurate even with a limited amount of known information. The Environmental Analysis Tool™ can accommodate this assessment during those early stages, as the minimum amount of information required to calculate the structure's carbon footprint is:

1. The number of stories (superstructure and basement).
2. The total framed area in the structure.
3. The structural system type.
4. The expected design life.
5. Site conditions related to design wind and seismic forces.

With this limited amount of input data, the program refers to a database containing the material quantities for an inventory of previously designed SOM structures. Statistical models are used which consider building height relative to low, moderate, or high wind and seismic conditions. The superstructure material framing options considered include structural steel, reinforced concrete, composite (combination of steel framing and concrete core), wood, masonry, and light gage metal framing. Foundation materials include reinforced concrete and steel. Key concepts of the Environmental Analysis Tool™ are illustrated in Figure 1.

The selected seismic resisting system is important to the carbon footprint over the life of the structure. The contribution of carbon related to damage from a Maximum Considered seismic event could easily account for 15%-30% of the total carbon footprint for the structure according to studies such as [Comber et al. 2012]. The Environmental

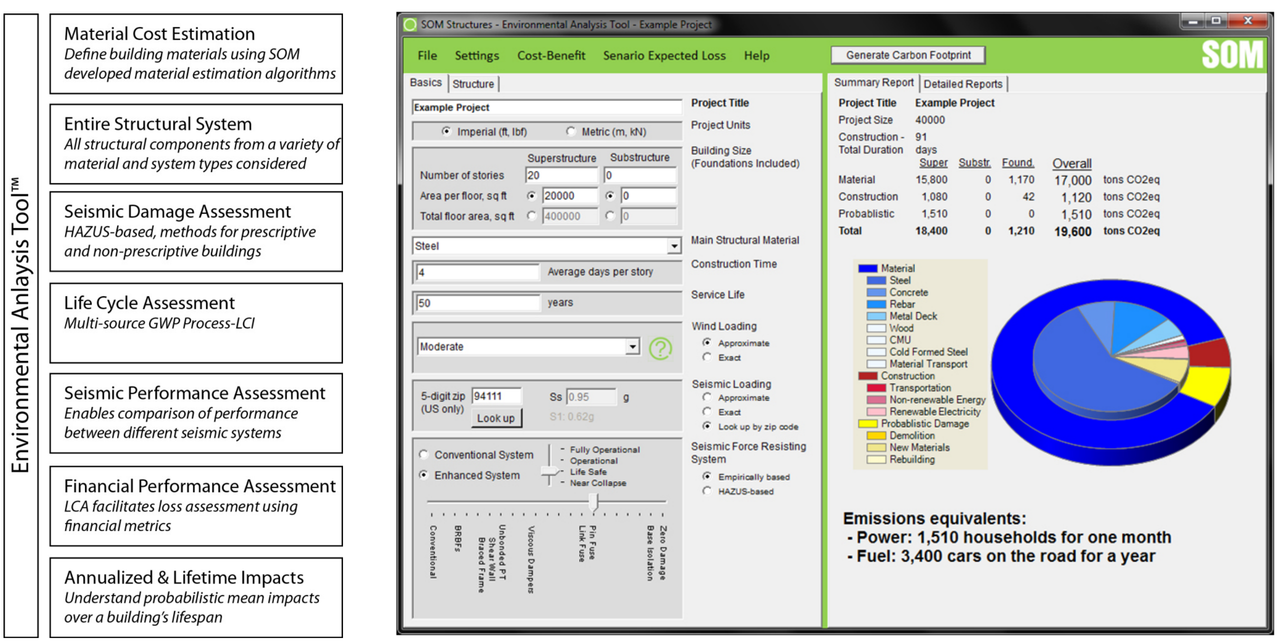

Figure 1: Environmental Analysis Tool™ - Component overview (left) and interface (right)

Analysis Tool™ utilizes HAZUS methods for probable seismic damage and embodied carbon of repairs, and reports this damage in equivalent carbon dioxide emissions over the anticipated life of the building.

The program uses this fundamental information to estimate the embodied global warming potential (GWP) associated with construction methods and duration, the fabrication and transportation of material, the labor required to build the structure, and laborers' transportation needs, among others. With this limited amount of information, an early assessment of the structure's GWP, measured in equivalent carbon dioxide emissions, can be performed. Program interface examples are shown in Figure 1. The program also allows for flexibility later in design by allowing users to override all inputs with project-specific values such as detailed material quantities, floor-to-floor cycle durations, transportation distances for all materials, etc.

Environmental Analysis Tool™ Program Details

Equivalent carbon dioxide emissions associated with the structural system of a building may be categorized as those resulting from the following three major components: (1) materials used to manufacture the structure; (2) construction activity; and (3) predicted damage due to seismic hazard.

The EA Tool™ considers the measurement of equivalent carbon dioxide emissions for a building structure. Equivalent CO2 is a common metric used to account for other greenhouse gases that contribute significantly to the total global warming potential (GWP) of the structure in question, weighted to the equivalent potential for global warming as carbon dioxide. An example is methane, whose GWP is 21 times that of CO_2. Therefore, total amount of methane is multiplied by 21 to convert to equivalent CO_2.

The EA Tool™ considers the first cost of these systems and performs an analysis of anticipated damage and costs over the structure's specified life to calculate the cost-benefit ratios of various enhanced seismic systems such as base isolation or buckling restrained braces. The cost-benefit analysis considers the annual rate of return, mean annual loss savings, and first costs.

SEAONC SDC Comparative Study Utilizing the EA Tool™

The present study employed the EA Tool™ to perform an LCA and compared the carbon accounting results with those obtained from the SEAOC study. The equivalent CO_2 impact of the case study buildings was compared from the three LCA tools. The present study utilized the "user-input material quantities criteria", see Table 1. These material quantities were based on the SEAOC study's bill of

Material	Units	Qty								
		CS-1	CS-2	CS-3	CS-4	CS-5	CS-6	CS-7	CS-8	CS-9
Superstructure										
Steel	psf/sf_tot				4.8	9.051	6.4	1.9		0.6
Concrete	cf/sf_tot	0.89	0.908	0.851	0.39584	0.39584	0.39828	0.1034	0.1	0.1
Rebar	psf/sf_tot	6.72	5.882	5.103	1.811259	1.1	1.1001	0.315	0.31	0.31
Metal deck	psf/sf_tot				2.2	2.2	2.2			
Wood Dim. Softwood Lumber	cf/sf_tot							0.0173	0.0359	0.06
Wood Panels: OSB	cf/sf_tot							0.026114		0.0459
Wood Panels: Plywood	cf/sf_tot							0.092586	0.0414	0.1341
Wood Glulam	cf/sf_tot							0.0768	0.51	0.079
Wood Timber Trusses	cf/sf_tot									
CMU	cf/sf_tot			0.252	0.2728					
Cold-Formed Steel incl Fasteners	psf/sf_tot							0.1203	0.3964	0.15
Foundation										
Steel	psf/sf_tot									
Concrete	cf/sf_tot	0.29	0.365	0.268	0.25632	0.21432	0.2272	0.2827	0.19	0.3
Rebar	psf/sf_tot	0.83	1.68	0.73	1.035	0.368593	0.93155	0.9643	0.5	0.57

Table 1: Bills of Materials Used in EA Tool™

materials [Court et. al. 2013]. Other inputs for transportation and construction for the superstructure, substructure, and foundation were taken to be the "system-generated default criteria" from the EA Tool^{TM}. To maintain consistency with assumptions made in the SEAOC study, the EA Tool^{TM} results presented below do not include the effects and emissions from the probabilistic seismic damage. As such, the demolition and reconstruction estimation methods inherent to the EA Tool^{TM} were not used.

Individual Building Descriptions

The following is a summary of the structural systems modeled in the EA Tool^{TM}. More detailed descriptions and floor plans are listed in [Court et. al. 2013] except in the case of the CS-9 building, which was not modeled prior to publication. Building and material specific assumptions made to accurately reflect the case study buildings within the framework of the EA Tool^{TM} are listed as applicable.

Concrete Special Moment Frame System CS-1:

Structural System: The concrete special moment frame design includes four 2- bay moment frames aligned around the perimeter of the building. Typical floor and roof slabs were designed as post-tensioned flat slabs. Columns were designed as square columns at all floors.

Foundation: Gravity footings are square spread footings. The perimeter moment frames are supported on continuous grade beams.

Concrete Shear Wall CS-2:

Structural System: The concrete shear wall design includes three C-shaped shear walls at the core of the building. Typical floors and roof slabs were designed as post-tensioned flat slabs. Columns were designed as uniform square columns at all floors. Typical floor and roof slabs were designed as post-tensioned flat slabs.

Foundation: Gravity footings are square spread footings. The C-shaped shear walls are supported on 3-foot thick mat footings.

Masonry Shear Wall & Concrete Floor System CS-3:

Structural System: The masonry shear wall and concrete floor building design includes masonry core shear walls and post-tensioned flat slabs at the roof and floors. Columns were designed as uniform square columns at all floors. Wall configuration is constant throughout the height of the building, though the thickness decreases at the upper floors.

Foundation: Gravity footings are square spread footings. The core shear walls are supported on 3-foot thick mat footings.

Masonry Wall and Steel Floor System CS-4:

Structural System: This building has masonry core shear walls that decrease in thickness at the upper floors. Gravity framing consists of steel wide-flange joists and girders, with a composite concrete over metal deck floor. Columns are all steel wide-flange sections.

Foundation: Gravity columns are supported on square isolated pad footings. Shear walls are supported on continuous grade beams.

Steel Special Moment Frame CS-5:

Structural System: This building has four 3-bay steel moment frames aligned around the perimeter of the building. Gravity framing consists of steel wide-flange joists and girders, with a composite concrete over metal deck floor. Columns are all steel wide-flange sections.

Foundation: Columns and shear walls are supported on spread footings designed based on the 3,000 psf allowable soil bearing.

Steel Buckling Restrained Braced Frame (BRBF) CS-6:

Structural System: This building has two single bay buckling-restrained braced frames aligned at each perimeter side of the building. Gravity framing consists of steel wide-flange joists and girders, with a composite concrete over metal deck floor. Columns are all steel wide-flange sections.

Foundation: Gravity columns are supported on square isolated pad footings. Braced frames are supported on grade beams spanning under each respective frame bay.

Light Timber with BRBF CS-7:

Structural System: The BRBF design includes four single-bay buckling-restrained braced frames. Each braced frame alternates between a "V" configuration and a "chevron" configuration up the height of the building, creating an effective two-story "X" configuration. Wide flange columns are used at the braced frame bays. Floor & roof framing consists of plywood over TJI joists spanning to glued-laminated girders. Concrete floor topping was used at each floor. Gravity columns are HSS sections.

Foundation: Gravity columns are supported on square isolated pad footings. Braced frames are supported on grade beams spanning under each respective frame bay.

Heavy Timber with Plywood Shear Walls CS-8:

Structural System: This building is composed of glued-laminated beams (GLB) and cross-laminated timber (CLT) floors supported on light-framed plywood shear/bearing walls. Typical floors and roof slabs were designed as a solid wood CLT panel floor system with concrete topping added for acoustic performance.

Foundation: Columns and walls are supported on 2'-0" thick spread footings.

Light Timber With Plywood Shear Walls CS-9:

Structural System: The plywood shear wall design includes four lines of shear walls in one direction and two lines of 4-shearwall segments in the opposite direction, all double-sided and at the core of the building. Typical floor framing consists of 1.5" concrete topping over ¾" plywood over 26" TJI joists at 16" o.c., framing between 8.75"x30" and 6.75"x27" GLBs at the interior and exterior, respectively. Typical roof framing consists of ½" plywood over 16" TJI joists at 24" o.c., framing between 6.75"x21" and 5.125"x18" GLBs at the interior and exterior, respectively. The GLBs frame into steel columns, HSS8x8 at the interior and HSS5x5 at the perimeter with 3/8" wall thickness at the 1st and 2nd floors and ¼" wall thickness at the 3rd floor and above.

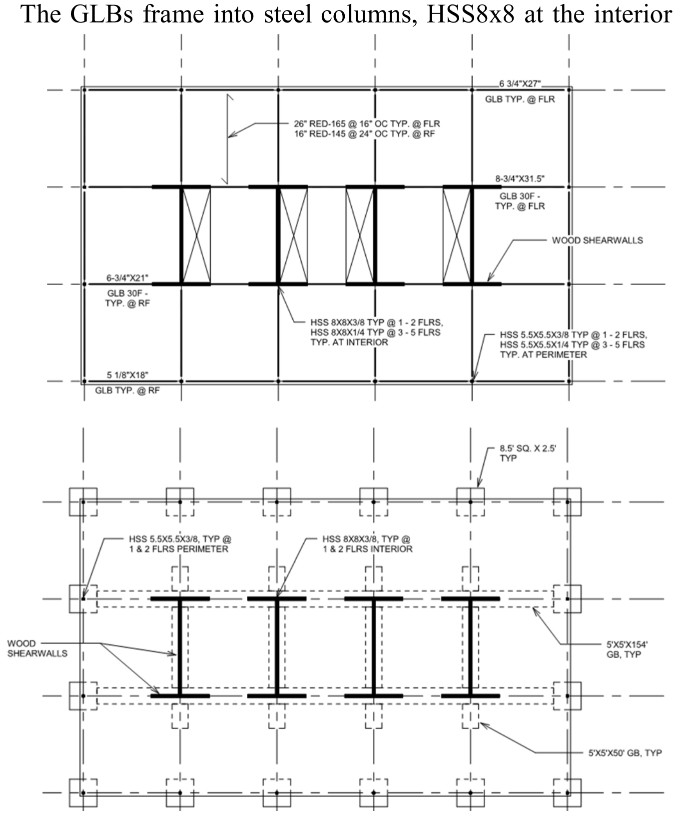

Figure 2: CS-9 Light Framed Wood Shear Wall Foundation & Typical Floor Plans

Slab-on-grade: Slab-on-grade was assumed to be 5" thick with 6x6 W2.9xW2.9 WWF.

Foundation: Footings were designed based on computer analysis to determine size, thickness and reinforcement, using 3,000 psf allowable soil bearing for design dead and live loads. The perimeter columns are supported on 8.5' square x 2.5' deep spread footings. The interior posts are supported by 5' wide x 5' deep grade beams, two lines of 154' lengths and four lines of 50' lengths, corresponding to the shear wall layout.

Schematic plan layouts for buildings CS-1 through CS-8 are available in [Court et. al. 2013]. Schematic plan layouts for building CS-9 are shown in Figure 2.

Modeling Assumptions

The following assumptions are inherent to the EA Tool™ and not available for adjustment by the user:

- 50 year service life. Note the Athena Impact Estimator assumes 60 years. This assumption, however, is applicable only to the estimate of environmental impacts directly attributable to building operations and seismic damage during its lifespan. Since these impacts are not included in results reported in this study, this difference between the programs has no bearing on the conclusions of this study.

As should be expected when comparing different analysis software programs, inherent differences in the user interfaces, underlying calculation methodologies, and structural system definitions entail that certain assumptions had to be made, and strategies utilized, to most accurately model the case study buildings in the EA Tool™. The following assumptions and approaches were applied uniformly to all EA Tool™ case study buildings in an effort to most accurately reflect the total materials usage and fabrication methods of the respective IE and Tally case study buildings:

- EA Tool™ requires input of wind and seismic loading to the building as structural performance objective. This input is used only to calculate approximate associated materials usage when allowing the EA Tool™ to pre-define the building's design. This option was not utilized for this study.

- EA Tool™ automated assumptions of material quantities based on limited building information as discussed above were not utilized. Rather, those pre-defined material inputs were overridden with exact inputs for each material to generate equivalent bills of materials to those utilized in the IE and Tally studies.
- All material inputs were entered using the EA Tool™ metrics of (material quantity) / (sf of total building area). Note this assumption becomes critically important when inputting foundation material quantities as the user may be tempted to input as (material quantity) / (sf of building footprint), which in multi-story buildings would cause drastic misrepresentation of the foundation impacts.
- Slab on grade materials were included in the foundations input of EA Tool™.
- "Low strength" concrete was assumed with 25% fly ash for all applications of concrete.
- A steel fabrication level of "average" was used for all structural steel elements.
- A construction time of 15 days/story was assumed. Note the EA Tool™ uses this information to account for construction emissions. This assumption was made to best approximate the IE's consideration of construction time.
- All concrete formwork that was included in the Athena IE study was entered into the EA Tool™ study as equivalent plywood and lumber materials.

The following approaches and assumptions were applied to the steel EA Tool™ case study buildings:

- Buckling-restrained braces in the CS-6 building were modeled as equivalent HSS, steel plate, and concrete material components.

The following approaches and assumptions were applied to the masonry EA Tool™ case study buildings:

- EA Tool™ only allows input of 8"x8"x16" CMU blocks. Where different CMU sizes were utilized in the Athena study, they were input to EA using total volume converted to an equivalent 8"x8"x16" block.
- CMU grout was not modeled explicitly in EA Tool™. Rather, the EA Tool™ inherent assumption of grout as a function of CMU volume was employed.

The following approaches and assumptions were applied to the wood EA Tool™ case study buildings:

- EA Tool™ does not allow input of most engineered lumber products, with the exception of glu-lam, plywood/OSB and trusses. As such, all engineered lumber products were broken out into their sawn lumber and plywood components for modeling. This approach was consistent with the approach employed in the earlier Athena study. Note that for some products used, e.g. CLT, this assumption does not accurately capture the additional impacts associated with adhesives and additional fabrication.
- Fasteners were not input into the EA Tool™ study. Rather, the EA Tool's™ inherent assumptions regarding fastener weight as a function of lumber input were utilized. Manufactured hangers were input as equivalent cold-formed sheet steel.
- Sawn lumber was input to EA Tool™ as volume of raw unplanned lumber dimensions, rather than final dressed dimensions. This assumption is consistent with that utilized in the Athena IE study.
- Buckling-restrained braces in the CS-7 building were modeled as equivalent HSS, steel plate, and concrete material components.

Observations and Comparisons

In processing the data from each of the three LCA packages, the SEAONC SDC felt it was important to compare both the absolute global warming impact results in addition to the relative values. The committee was interested in how close each of the software packages would be in estimating overall carbon impact of the structural systems to determine how important the selection of the LCA tool was to the relation to the overall results (including operational carbon impacts). Additionally, since LCA is used as a relative tool for comparison between design scheme options, the committee was interested to compare the relative differences between structural systems for each tool.

Lastly, the committee was curious to study the variation in the results to see if any specific materials or systems were more susceptible to variation than others.

The following sections discuss the trends that were observed in this study and the results are evaluated.

Comparison of BOMs Used in EA Study

The bills of materials used in the present study are depicted in Table 1. Generally, the quantities compare across the buildings, as should be expected.

When reviewing the bills of materials, the most significant thing of note is the units required for input to the EA Tool™. Since units are generally requires as material volume per square foot, the numbers required for input are very small. In many cases, accuracy is required to the hundredth or perhaps the thousandth of a unit. This characteristic may be a potential source of inaccuracy in inputting materials to the EA Tool™. One reasonable alternative might be to input the materials as a unit of mass per square foot, as this is a unit that most practicing structural engineers are accustomed to working with. However the committee acknowledges the potential for user assumptions around input material mass to inaccurately skew the final output of the LCA.

Comparison of LCA Results for Various Athena IE Versions

The Athena Sustainable Materials Institute has updated the IE multiple times since the initial SEAOC SDC study publication in 2013. Variation in the LCA results was observed to differ depending on the version of the Athena IE software used. This variation is a result of the LCI data for Athena's beyond building life (or end of life) impacts, which most significantly changed from version 5.0 and 5.0.0125. Figure 3 shows the global warming potential for the case study buildings for three different versions of the Athena IE.

If this data is compared without including the beyond building life stage, the GWP numbers are more consistent among the versions. The discrepancy among the versions should be taken in context with the assumptions made/LCI data used in the particular version. As LCA is still a young science, the industry standards still are developing. The LCA practitioner needs to be aware of this when performing an LCA and be able to put the LCA results in the right context and not compare results from one version to another.

Athena IE vs. SOM EA Tool™

There are substantial differences in the GWP results between these two tools that warrant further study. As seen in the normalized results in Figure 4, Athena IE results show significant variation between the concrete and wood systems with the latter being only 25-30% of the former's total GWP. While the SOM EA Tool™ also shows that the wood

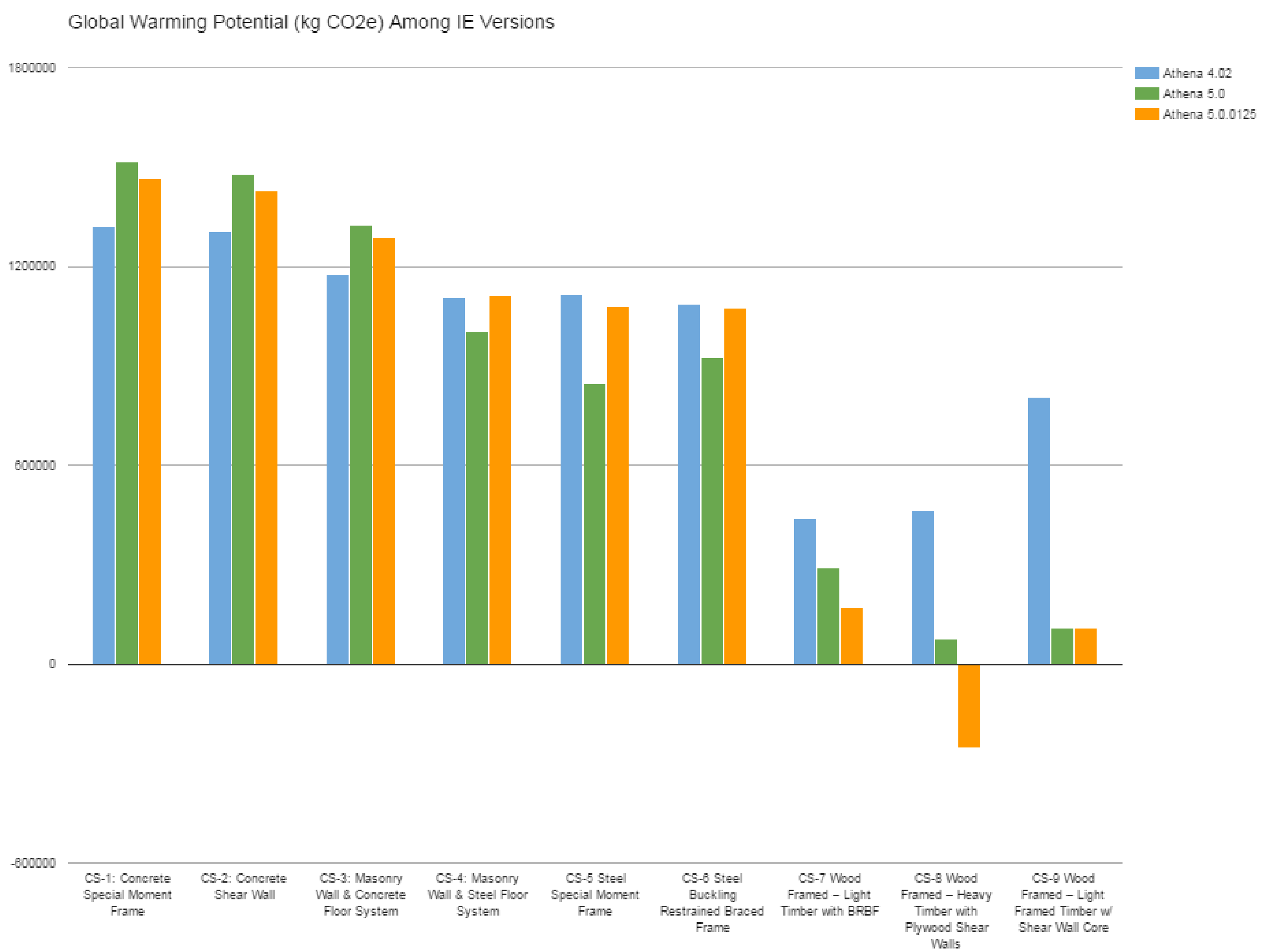

Figure 3: Global Warming Potential (kg CO2e) Among IE Versions

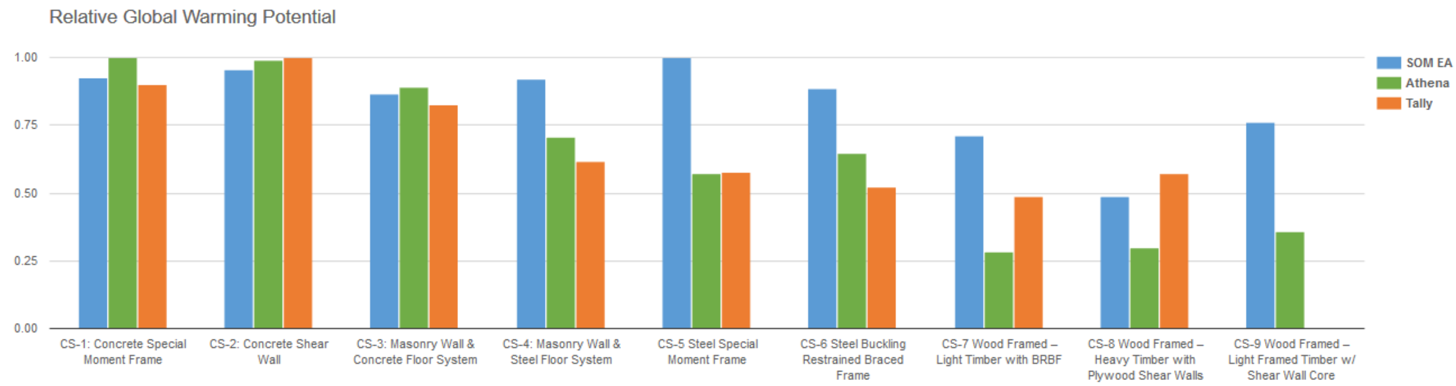

Figure 4: Comparative Results – Relative Global Warming Potential (each LCA Tool normalized to itself)

systems have a lower impact for this prototype building, the reduction in GWP is significantly less and ranges from 50-75% of the highest impact system (in this case CS-5, the Special Steel Special Moment Frame). Also, it should be noted that the IE tool adds an extra 5-10% waste factor in their LCA where the EA Tool™ does not.

Athena IE vs. Kieran Timberlake Tally

Athena IE and Tally are in close alignment on all systems with the exception of the wood systems as shown in Figure 5.

SOM EA Tool™ vs. Kieran Timberlake Tally

EA Tool™ and Tally track closely on concrete and timber systems, but vary on steel systems as shown in Figure 5.

Athena IE vs. SOM EA Tool™ vs. Kieran Timberlake Tally

As seen in Figure 6, there is broad agreement, and little variation between the three tools for Concrete and Masonry construction impacts. However, for structural steel and wood buildings, the selection of the specific software package could lead to significantly different results. This study found as much as 40-50% differences in the timber systems' results. This may be less a function of an inherent difference in each tool's LCA process for timber, but more reflective of the fact that there is a relatively fixed margin for error between the LCA processes. As the overall impact is reduced (as the trend for wood systems across all three LCA tools shows), the variation between the LCA methodologies becomes a larger portion of the average values. More study is necessary to determine whether the primary cause for the variation between the systems is purely a statistical by-product or is fundamental to the assumptions within the LCA tools' methods.

The SOM EA Tool™ shows relative parity between environmental impacts of systems. There was only 19% standard deviation, compared with Athena's 25% standard deviation. This could be a function of the relatively limited life-cycle inventory, and the contributing size/scale of wood buildings from SOM's database. The inclusion of seismic damage in the life-cycle carbon impacts is an incredibly valuable feature, and should not be discounted when compared to other LCA tools in this study.

The Athena IE shows significantly more carbon benefits for wood systems than the other two tools. This is mainly due to how the IE accounts for wood's carbon sequestration. More study is needed to understand the underlying assumptions

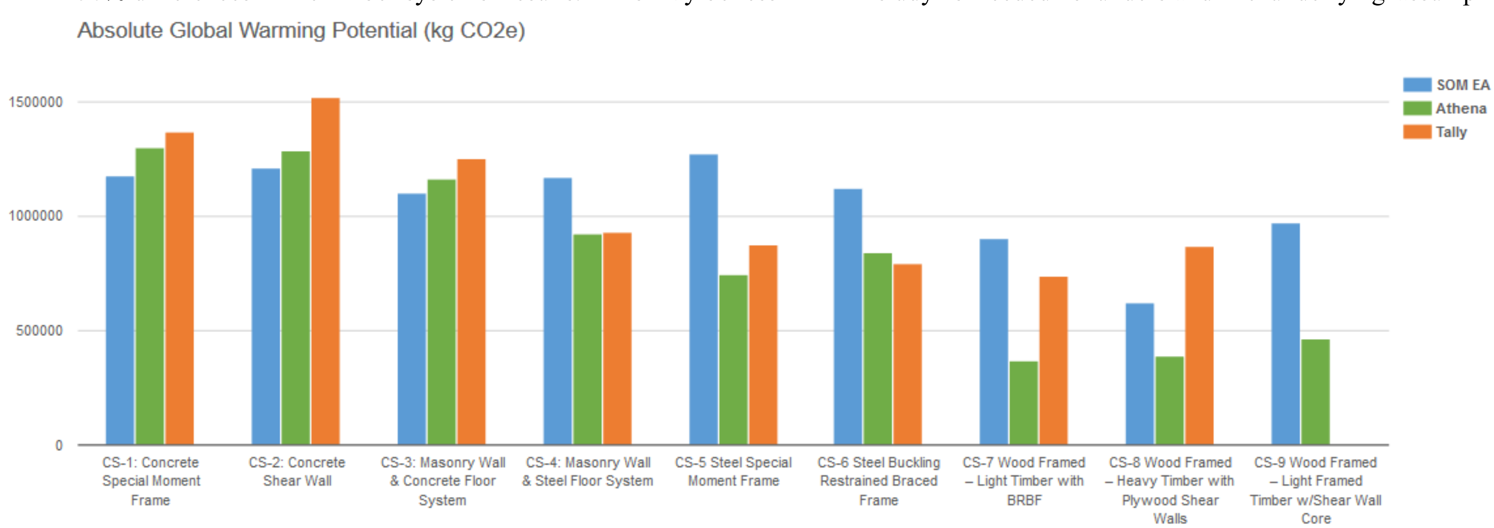

Figure 5: Comparative Results – Absolute Global Warming Potential (kg CO2e)

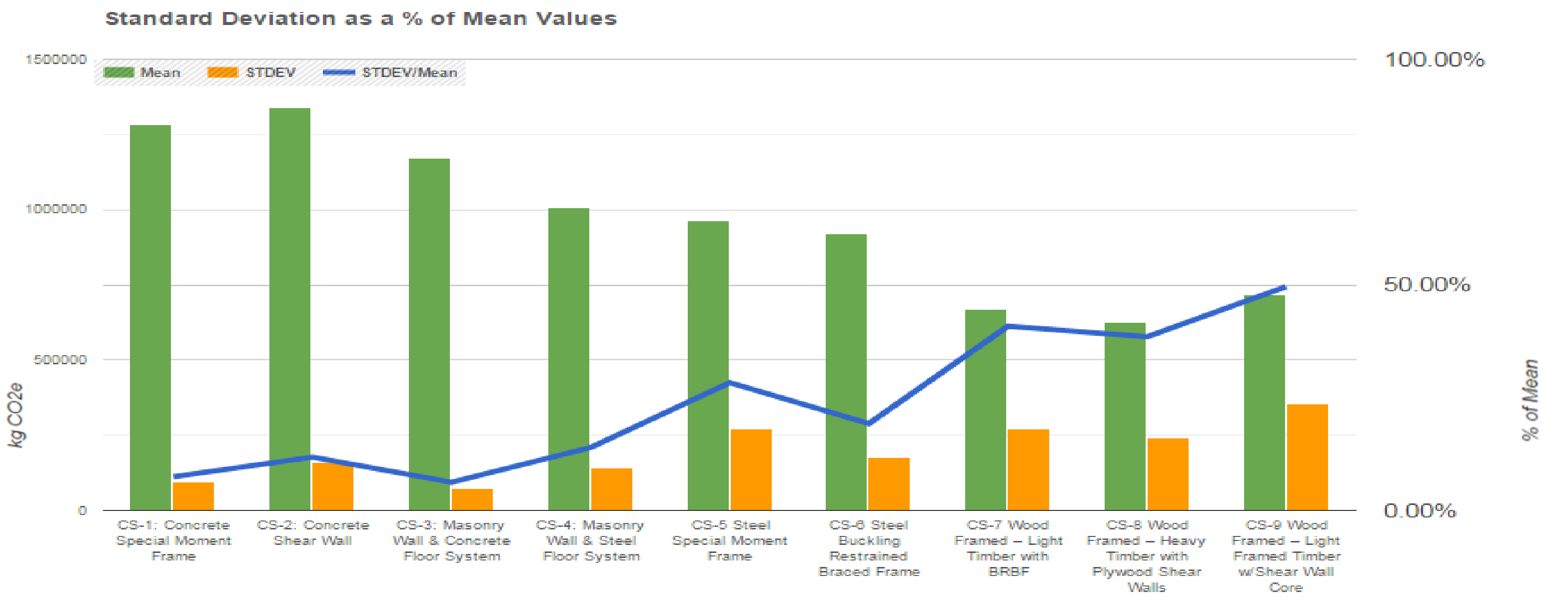

Figure 6: Mean Results and Standard of Deviation as a % of Mean Values

for each software package to understand the root cause for the differences.

Conclusion

It should be noted again that the scope of this study is limited to the environmental impact from the structural systems only. Best LCA practices demand that these results be taken in the context of the overall building LCA. For example, while the results of this study show on average a lower GWP for steel systems than concrete systems, this does not take into account potential reductions in finish materials or improved life-cycle operational energy through the use of thermal mass strategies. Therefore, the committee does not recommend any conclusions be drawn about the relative benefits between one structural system or another based on this study. Rather, the intent is to understand and document the variations between LCA tools currently available to structural designers and understand the importance of an LCA tool's assumptions.

At the beginning of this study, the committee had hoped to demonstrate that, while there may be variations in the absolute results between the LCA tools, the relative trends and values between systems within a single LCA platform were consistent. As is shown in Figure 4 however, there are substantial relative disparities in the results that could lead to different design decisions if used on a project.

The committee recommends further study to determine the source of the variations between the LCA tools, and provide design teams with a better understanding for the most appropriate LCA tools for use on future projects. Additionally, it is recommended that design decisions be based on relative comparisons between a single LCA tool's results, and discourage the use of absolute values or comparison across LCA tools.

Despite the complexity of performing an LCA, LCA is a powerful methodology in offering an approximate measurement of environmental impacts for comparative purposes. LCA gives structural engineers a scientific way to measure and reduce the environmental impact of the structures they design. While it is still a developing practice, LCA allows design teams to understand the environmental tradeoffs of their design decisions, which allows for more comprehensive decision-making.

References

Athena Sustainable Materials Institute, ATHENA Impact Estimator™ [Online] www.athenasmi.org.

Clinkenbeard, John P. Map Sheet 52 – Aggregate Sustainability in California. 2012. California Geological Survey Department of Conservation. Sacramento.

Comber, Matthew V.; Poland, Chris; Sinclair, Mark. Environmental Impact Seismic Assessment: Application of Performance-Based Earthquake Engineering Methodologies to Optimize Environmental Performance. 2012. Proceedings: American Society of Civil Engineers – Structural Engineering Institute Structures Congress. Chicago, IL.

Court, Anthony B., Podesto, Lisa, and Harburg-Petrich, Patti. SEAOC LCA Study Comparing Environmental Impacts of Structural Systems. In the 2013 SEAOC Convention Proceedings (pp 137-153). San Diego, CA.

Court, Anthony B., Podesto, Lisa, Harburg-Petrich, Patti, & Stringer, Megan. Using Life Cycle Assessment to Compare Environmental Impacts of Structural Systems – Structural Engineers Association of California Sustainable Design Committee Case Study. Presented at the 2014 Portland State University's Sustainable Structures Symposium. Portland, OR.

Kestner, Dirk M., P.E., Jennifer Goupil, P.E., and Emily Lorenz, P.E., eds. *Sustainability Guidelines for the Structural Engineer*. Reston: American Society of Civil Engineers, 2010. Print.

Kieran Timberlake. Tally. 2014. www.choosetally.com.

SOM. Environmental Analysis Tool™ Report and User Guide. 2013. www.som.com.

Stringer, Megan, & Yang, Frances. Life Cycle Assessment for Structural Engineers. In the 2013 SEAOC Convention Proceedings (pp127-132). San Diego, CA.

"Structures and Carbon How Materials Affect the Climate." ASCE-SEI Sustainability Committee. Ed. Mark D. Webster, P.E. American Society of Civil Engineers, 2012. Web. 11 Dec. 2012.