Assessment of embodied carbon in timber and concrete building systems

by

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Abstract

This report analyzes and compares the embodied carbon impacts of timber and concrete structural systems through the cradle to gate phases of design and construction (A1-A5, Table 1). These phases are defined in the within the report. Furthermore, the report examines the industry's current stance on sequestered carbon and reduction techniques. This report serves to establish a better understanding of the impacts that arise from unmanaged greenhouse gas emissions, as well as provide guidance on how to reduce the embodied carbon within a timber or concrete structural system.

In the analysis, the superstructures were evaluated in two main phases (A1-A5, Table 1). The first phase, known as the product phase, included all processes necessary to ready the building materials for construction. The construction phase followed and included all operations needed to install the superstructure at the site. Using the information in this report, an embodied carbon estimating spreadsheet was created. This spreadsheet confines the information to a user-friendly platform capable of calculating embodied carbon quantities using inputs provided by the user. The information allows the user to pinpoint areas of concern within their design and compare them to alternative solutions.

To compare the two building superstructures, a sample calculation was computed using assumed design criteria of a one-story building with a 20,000 ft^2 footprint. The sample resulted embodied carbon masses of 73,294 kg for the timber system and 186,482 kg for the concrete system, yielding timber as the more carbon-efficient structural material for this building.

To reduce embodied carbon within structural systems, carbon sequestration provides the greatest potential. Carbon sequestration is the process of capturing and storing carbon dioxide from the atmosphere. Although carbon sequestration has occurred naturally for many

years, scientists and engineers are finding new ways to incorporate this concept. These methods can include bioengineering, as well as artificially placed carbon. With the continued advancement of sequestering techniques, the idea of carbon neutral building materials continues to grow in relevancy.

The material analysis in this report includes a more detailed breakdown of embodied carbon within structural systems than the currently available estimating tool from the Structural Engineering Institute. The utilization of this report allows an industry professional to analyze where embodied carbon is sourced in their project and determine what alternatives would aid in reducing the carbon footprint. As the industry advances in sequestering technologies, the combination of reduction efforts will continue to increase its effectiveness over time.

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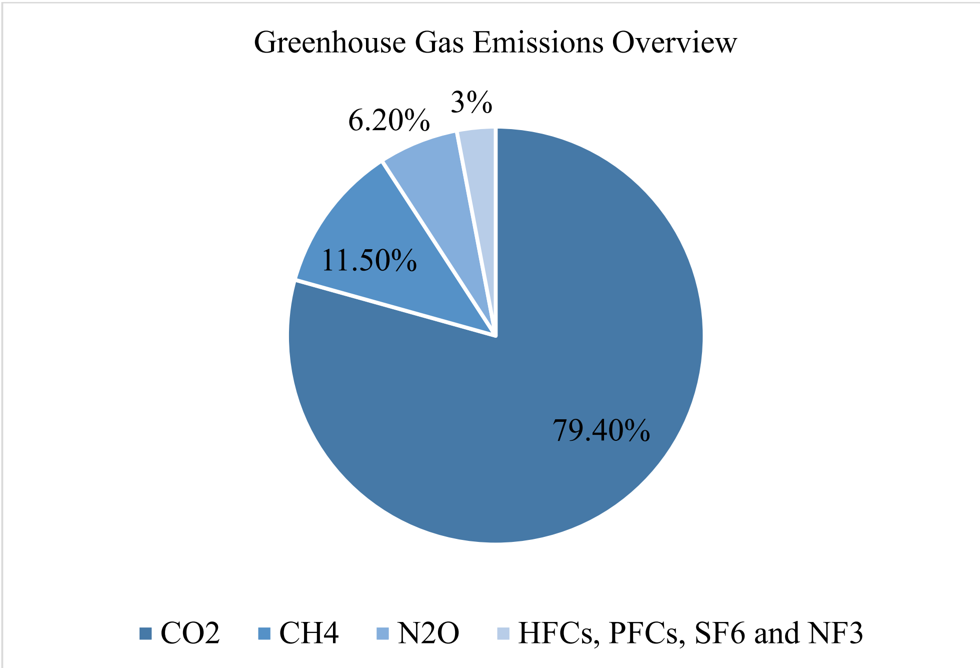
Introduction

Earth's natural processes are no longer sufficient to combat human disruption. Due to modern advancements in society, greenhouse gases are releasing faster than the planet can naturally offset. This excess continues to disrupt the natural balance of the atmosphere year after year, and the long-term effects for human well-being are still unknown. Greenhouse gases are known to allow radiation in from the sun but absorb the heat reflecting out. Therefore, a higher concentration of these gases will result in more heat reflected to the Earth's surface. Although these gases are necessary to prevent the planet from freezing, too large of a concentration may lead to irreversible planetary effects. Some of these results include higher global temperatures, acidic bodies of water, and loss of coastline due to rising sea levels resulting from the melting of polar ice caps. To effectively provoke change, an understanding of what these greenhouse gases are and where they come from is crucial.

Figure [1] shows the breakdown of greenhouse gases from a 2021 report. The report identifies that carbon dioxide makes up roughly 79% of all greenhouse gas emissions in the United States. Given the magnitude of this portion, reducing the impact of carbon dioxide should be a top priority. With 39% of carbon emittance coming from buildings and construction each year, there is great potential for the building industry to reduce global carbon emissions. Within the building industry, carbon emission is separated into two groups: operational and embodied carbon. Operational carbon refers to the energy needed to keep the building in function. This can include processes such as heating, water distribution, lighting, and others. Embodied carbon results from the creation, maintenance, or demolition of the building. Operational carbon reduction techniques have come a long way since first gathering attention in the 1980s. There are many equipment modifications and design techniques that have been implemented and proven effective in building

Figure 1. Greenhouse Gas Emissions Overview
(from epa.gov)



design for reducing operational carbon. Unfortunately, fewer methods are known for reducing embodied carbon in buildings. One reason the industry has seen little advancement is due to the extra expense associated with this application. Typically, contractors/owners are looking for the fastest or most efficient means of construction to ensure their budget is in check. Since carbon reduction efforts are not typically accounted for in the bidding process, the cause is ignored. This report serves to provoke change in the industry and provide additional guidance for how project methods can be adjusted to lessen the impact of embodied carbon emissions.

The research collected in this report will observe the embodied carbon processes of timber and concrete superstructures. It will specifically analyze the 'cradle to gate' processes. This timeline is shown in Table [1] as the product and construction phases of design (Module A1-A5). This timeframe includes the embodied carbon footprint up until the building is operational.

Although the reusability of materials will be considered, the operational and demolition phase are not the primary focus for this report. When examining carbon emissions, carbon monoxide and carbon dioxide will be the areas of focus. Other makeups containing carbon, such as hydrocarbon, will not be included for simplicity in comparisons. Upon completion of this report, a detailed template of data to compare timber and concrete structural systems will be provided. Users will also be able to pinpoint the process in construction where high amounts of embodied carbon are developed. This information will allow users to optimize their carbon efficiency by using design alternatives where there are areas of concern.

Table 1. Embodied Carbon Phases
(from gettingtozeroforum.org)

Stage	Product			Construction		Maintain and Use	End of Life	Beyond the Lifecycle
Phases	Cradle to Gate					Gate to Grave		
Carbon	Embodied					Embodied/Operational	Embodied	
Description	Extract Raw Materials	Transport to Factory	Manufacture Products	Transport to Site	Construct the Building	Use and Maintain the Building	Demolition	Reuse/Recovery
Module	A1	A2	A3	A4	A5	B1-B7	C1-C4	D

Definition of Terms

Embodied Carbon	Greenhouse gas emissions associated with upstream (extraction, production, transport, and manufacturing) stages of a product's life.
Greenhouse Gas Emission	Emission from any gaseous compound (such as carbon dioxide or methane) that absorbs infrared radiation, traps heat in the atmosphere, and contributes to the greenhouse effect.
Net Zero	The total impact of all components of the structural system net to a zero embodied carbon impact when considering all stages of a building's life cycle.
SE 2050 Commitment Program	A comprehensive program designed to ensure substantive embodied carbon reductions in the design and construction of structural systems by the collective structural engineering profession.
Carbon Sequestration	Any of various methods or processes for capturing and storing carbon dioxide from the atmosphere.
Cradle to Gate	Model in the life cycle assessment spanning from raw materials extraction to the point it reaches the consumer.

Literature Review

The largest push for carbon-neutral buildings in the U.S. is the Structural Engineers 2050 Commitment Program (SE 2050). This concept was widely introduced by the Carbon Leadership Forum in 2016. The challenge outlines the need for buildings with net-zero embodied carbon structural systems by the year 2050. “It is well documented that we must be a carbon neutral society by 2050 if we are to avoid irreversible detrimental impacts to our environment” (SE 2050, 2019). In 2018, the challenge was presented to the Sustainability Committee of the Structural Engineers Institute (SEI) of the American Society of Civil Engineers (ASCE). As one of the largest structural engineering groups in the United States, this body recognized a responsibility for them to spread knowledge and collaboration of this issue throughout the nation. In the following years, ASCE continued to provide support for this cause and created a database for firms to submit annual embodied carbon reports to show their commitment to the program. Part of this commitment includes an agreement to participate in the Embodied Carbon Action Plan. The plan encourages the firm to support staff education efforts, document reduction strategies used, and track the global warming potential of their projects. Over the first two years of the program, 101 firms signed their commitment and over 250 projects were submitted to the database. To track global warming potential, SEI has published an embodied carbon estimating tool known as the Embodied Carbon Order of Magnitude (ECOM) (SE 2050, 2019). The tool estimates the embodied carbon accumulation based on the quantity of materials and square footage of the project. Although this estimator provides a decent baseline, its broad scale restricts its usefulness for determining where reductions should be considered. Other than reducing the material quantity needed, there is no way of adjusting construction methods for a lower emission value. Without a more specific embodied carbon calculator, the industry will have little direction to reach SE 2050’s goal.

This report will provide a detailed calculation of the embodied carbon within timber and concrete superstructural systems. Using this template, firms will be able to see how each component of their work adds to the total carbon footprint of their project. This overview will help increase understanding of embodied carbon and advance efforts to help manage this process.

The decision to compare timber and concrete structural systems was derived from two ideologies. The first deciding factor was material use. With studies showing concrete to be the most widely used building material in the world, its importance in this research was deemed fundamental. The second ideology was determined by material importance. When determining the second material to compare to concrete, two building products were recognized as the most relevant candidates: steel and timber. Steel is a very commonly used material due to its structural advantages of elastic capability and uniformity. However, sequestered carbon potential led to the decision of selecting timber over steel in this document. Since one of the overarching objectives of this research is global embodied carbon reduction, carbon sequestration was determined to be an important topic for this report. Although steel was not selected as a main material for this research, some components will be included due to the reinforcing steel found in concrete structural systems.

Sequestered Carbon

Carbon sequestration is "the process of capturing, securing, and storing carbon dioxide from the atmosphere. The idea is to stabilize carbon in solid and dissolved forms so that it doesn't cause the atmosphere to warm" (CLEAR, 2019). The Structural Engineering Institute confirms this description by listing it as a method of "the more permanent removal of carbon, for example in chemical reactions that lock the carbon into the molecular matrix of a material" (Achieving, 2020). The most known products to do this are trees and plants. These organisms soak up carbon dioxide and convert it to energy and matter through photosynthesis. This gives an extreme benefit to timber systems with the opportunity to reduce embodied carbon as the tree grows. When the tree is cut to use as lumber, the carbon remains locked in the tree until the wood decomposes. Although the carbon is not released right away, there is still a negative effect caused by cutting down trees. Each tree removed from the ground results in a loss of future carbon sequestration since the tree does not continue to grow after it is cut. Therefore, responsible timber harvesting is very important for ensuring the replacement of trees that are taken down.

Although carbon sequestration is not a permanent solution, it is still considered an important part of yearly net-zero goals. The process traps carbon in materials where it cannot easily escape. Even when the building is later demolished and the material is thrown in a scrap yard or landfill, the carbon will not be released until it is decomposed. If the material is buried before decomposition, the carbon will stay trapped even longer underground. The reason this works effectively is due to the soil's ability to sequester carbon itself. Once the material is decomposed below grade, the carbon will stay contained until it is disturbed by an outside force. An example of this disturbance is excavation work. The disturbed soil in this case would release carbon back into the atmosphere. Since the carbon emission of this future release will be accounted for at the time of disturbance, carbon sequestration techniques are considered to result in negative emissions on a year-to-year basis. One could argue that sequestering efforts are temporary and will only push the greenhouse gas emission issues into the future. However, the idea is to reduce current emission levels to provide time for technology to innovate further. The hope is to allow more time for research and innovation to reach levels of carbon neutrality.

To determine the mass of sequestered carbon in a timber structure, the dimensional information from the logging process is needed. Per a publication by the University of New Mexico, the rate of carbon sequestration of a tree can be estimated using the total weight of the tree and the moisture content. Equation [1] lists how to determine the green weight of a tree using these values. Once the green weight of the tree has been computed, the dry weight will need to be figured. The dry weight neglects moisture within the tree since this matter will not aid in carbon sequestration. If the moisture content is unknown, an industry average of 27.5% has been provided. Once the dry weight is found, Equation [2] can be used to determine the rate of carbon sequestration.

Equation 1. Average Green Weight of a Tree
(from unm.edu)

Green Weight of a Tree (lbs) =	1.2*W	
W:	Above-ground Weight of the Tree	
	If D < 11 in	$W = 0.25D^2H$
	If D ≥ 11 in	$W = 0.15D^2H$
D:	Diameter of the Trunk (in)	
H:	Height of the Tree (ft)	

Equation 2. Sequestered Carbon in Trees
(from unm.edu)

CO_2 Sequestration Rate ($kgCO_2/yr$) =	[(W)*(C)]/(A)
W:	Dry Weight of the Tree (kg)
C:	Carbon Content of the Tree (%)
A:	Age of the Tree (years)

The future of carbon sequestration is promising. Through bioengineering, studies are finding ways to increase the rate of carbon absorption over time. Although this research is still early in development, genetic manipulation is not a new concept in timber products. For many years, trees have been altered to yield higher stress tolerances. This past success brings optimistic efforts to increase the carbon absorption of trees in the future. An example of these efforts can be seen through a California biotech company's poplar tree study. This study examined the carbon absorption of genetically engineered fast-growing poplar trees. When compared to a control group of normal poplar trees, the trees with altered genes grew at a rate more than 1.5 times faster than the control group. Included in this increased growth rate was a larger rate of carbon absorption due to the increased tree volume. This research opens the door for many other possibilities of carbon efficiency for wood products.

Fortunately, carbon sequestering efforts have not stopped with timber. Since concrete is the most widely used building material in the world, it has potential to create a large impact in global emissions. The most successful method of doing this thus far is carbon dioxide mineralization. This process involves capturing carbon dioxide through Direct Air Capture (DAC), a technology able to remove carbon dioxide emissions directly from the atmosphere, and converting it into carbonates. These carbonates can then be used to supplement or replace aggregates and other components within concrete. This utilization stores carbon within the material until decomposition. Given the applicability of this process to other materials, this method could lead to other future solutions for reaching a carbon neutral environment.

Methodology

This report uses a cumulative approach through its chapters by introducing the summation of embodied carbon through each material's lifetime. After each phase of the materials' assessment is concluded, an example calculation is provided using the findings of the report. The final sections examine how sequestered carbon and reduction strategies could be used to produce net-zero embodied carbon structural systems.

The information collected in this document utilized a positivism research philosophy with an inductive approach. This philosophy was selected due to its direct focus on numerical data rather than theory. Utilizing a cross-sectional time horizon, existing data sets were collected using various credible sources. Data analysis procedures included separating greenhouse gas emission values by their chemical compounds to compare the amounts of carbon separately. This step was deemed necessary due to the discrepancy of reported values in carbon monoxide and carbon dioxide. The main limitation of this research was a lack of history within the topic. Although global warming potential has been rising for centuries, the push for embodied carbon reduction is a relatively youthful concept. Due to the lack of history on this subject, additional time was needed for source collection. Once this setback was overcome, viable references were found. This methodology yielded a thorough examination of current embodied carbon statistics and aims to serve as a credible resource for the future.

Results

Timber Product Phase

The first portion of the embodied carbon life cycle assessment of timber structural systems is the product phase (A1-A3, Table 1). This phase begins with the logging process in the forests. A great amount of work goes into this process including the transportation of employees to and from the site, as well as freight trucks for the material. After the logging process is complete, timber is hauled to the sawmill. The mill is where the timber will be debarked and cut to its nominal specifications, followed by drying processes. After this process is completed, the lumber will typically travel to a treatment plant where it will be impregnated with preservatives and/or fire retardants. Once these processes are complete, the lumber is ready for installation and the product phase is complete. To examine the embodied carbon within this portion of timber's life cycle, many sectionalizations must be made to break up the process into measurable components.

The first part of the carbon emission process to consider is the worker transportation to and from the logging site. The methods of travel for these employees typically involve small trucks (pickups) and passenger vehicles. Over the years, the Environmental Protection Agency (EPA) has consistently restricted the allowable greenhouse gas emissions vehicles are allowed to produce during travel. These restricted values are provided in tiered lists with a larger tier number representing a more recent standard. Last updated in 2014, the Tier 3 standard currently governs for newly produced vehicles; however, Tier 2 vehicles are still commonly found. This standard restricts the amount of smog a vehicle is allowed to produce characterized by a bin rating. The bin rating clarifies how carbon-friendly the vehicle is and it is based on emission values found during testing. See Table [2] and [3] for the current emission standard tables. By utilizing the data outlined

Table 2. Tier 3 Emission Standards
(from epa.gov)

Standard	Carbon Monoxide Emission Limits (grams/mile)
Bin 1	0
Bin 20	1
Bin 30	1
Bin 50	1.7
Bin 70	1.7
Bin 125	2.1
Bin 160	4.2

Table 3. Tier 2 Emission Standards
(from epa.gov)

Standard	Carbon Monoxide Emission Limits (grams/mile)
Bin 1	0
Bin 2	2.1
Bin 3	2.1
Bin 4	2.1
Bin 5	4.2
Bin 6	4.2
Bin 7	4.2
Bin 8a	4.2

in the EPA's provided tables, the rate of carbon monoxide production can be documented. Carbon dioxide emission is directly related to the fuel economy of the vehicle. The EPA states carbon dioxide is expelled at a rate of 8.887 kg CO_2 per gallon of gasoline-fuel burned and 10.18 kg CO_2 per gallon of diesel-fuel burned. The product of fuel burned and the corresponding rate will yield the total carbon dioxide emission for the travel. If any of the employees happen to be driving electric vehicles, the previously discussed computation will not apply. Electric vehicles are unique to fuel burning vehicles in the sense there is no direct emission from the vehicle. Instead, embodied carbon is accumulated during the manufacturing of the battery and the power generation processes at the power plant. The Energy Systems Division of the Argonne National Library has published figures displaying the greenhouse gas breakdown for various types of batteries within the cradle to gate stages. Table [4] and [5] display the emissions responsible for the creation of lithium-ion and nickel-metal hydride batteries; the most-common types of battery used in electric vehicles. Since the values provided do not consist of a rate based on usage, the total embodied carbon of the battery would need to be divided by the expected lifetime of the battery to acquire an emission rate to be used in the calculations. It is important to note this source utilizes multiple research studies and the values have been averaged to a standard rate. The average rate is what has been selected for this research. To account for the electricity generation at power plants, information from the U.S. Energy Information Administration was utilized. This source lists a rate of .39 (kg CO_2/kWh) for utility-scale electric power plants. This rate will be applied for all electric vehicle use in this report.

The following part of the carbon emissions process to consider in timber harvesting is the equipment used at the logging site. The most common piece of hand-held equipment used for

Table 4. Cradle to Gate Nickel-Metal Hydride Emission Rates
(from anl.gov)

Battery Type	Carbon Monoxide (gCO/kg battery)	Carbon Dioxide ($kgCO_2$/kg battery)	Reference
NiMH	0.34	1.02	Rantik 1999[a]
	4.5	14.8	Gaines et al. 2002
	--	15	Ishihara et al. 1999
	2.1	8.3	GREET 2.7
	3.9	10.3	Rydh and Sanden 2005[c]
	7.5	19.5	Rydh and Sanden 2005[c]
Average	4.5	13.6	

Table 5. Cradle to Gate Lithium-Ion Emission Rates
(from anl.gov)

Battery Type	Carbon Monoxide (gCO/kg battery)	Carbon Dioxide ($kgCO_2$/kg battery)	Reference
Li-ion	--	18.2	Ishihara et al. 1999
	1.8	7.2	GREET 2.7
	4.3	12.1	Rydh and Sanden 2005[c]
	6.4	18.1	Rydh and Sanden 2005[c]
Average	3.0	12.5	

logging is the chainsaw. Although this is a smaller device, its frequent activity adds up to a substantial amount of exhaust emission. Using Equation [3] from the EPA, a carbon monoxide total can be determined for the chainsaw using the power produced, length of activity, load factor, and emissions factor. Other non-road fuel-powered equipment, such as front-end loaders can utilize this equation as well. One of the most useful parts of this equation is the load factor. This fraction acknowledges the equipment's engine will not be performing at 100% power the entire time of its task. Since the calculation represents the exhaust rate at full power, the factor is used to rid the time the engine spends at idle. To determine the carbon dioxide production, the previously introduced values from the EPA can be used based on the gallons of fuel burned. Once the loader finishes placing the logs on the freight truck, the members are ready for transportation to the sawmill.

Equation 3. Exhaust Emissions of Nonroad Engines
(from epa.gov)

Emissions (gCO) =	(Power)*(LF)*(A)*(EF)
Power:	Average Power (hp)
LF:	Load Factor (fraction of available power)
A:	Activity (hrs)
EF:	Emissions Factor (gCO/hp-hr)

The tables provided for greenhouse gas emissions in vehicles cannot be used for freight truck transportation. Standard passenger vehicles have been averaged to utilize a singular emission rate due to the relatively consistent load they carry. However, the exhaust rate of a freight truck has a large variability based on the weight it is transporting. For example, on the way to the logging site, the only load being transported is that of the truck and trailer itself. Whereas the trip from the logging site to the lumber mill could carry several additional tons of loading due to the logs. Since the carbon emission rate is very different in these scenarios, a different formula is needed with a load factor. Using Equation [4] from a publication by the Environmental Defense Fund (EDF), the carbon emission of a freight truck can be computed. This formula utilizes the distance traveled, emission factor, and load of the truck to equate the embodied carbon used during the trip. Generalized freight truck emissions factors are provided by the EDF. This organization lists 178 grams of CO_2 per metric ton-mile as the average freight truck emission factor. After plugging this factor into Equation [4], the carbon dioxide associated with this transportation can be calculated. After the logs are delivered to the sawmill, the milling process can begin.

Equation 4. Exhaust Emissions of Freight Transportation
(from business.edf.org)

Emissions (gCO_2) =	(D)*(W)*(EF)
D:	Distance of Travel (miles)
W:	Weight of Shipment (short ton)
EF	Emissions Factor (gCO_2)/short ton-mile)

The milling process uses many forms of large machinery to grade and cut the logs to correct shapes and sizes. A carbon footprint summary of these processes has been provided by the Finnish Sawmill Association. The results yield a carbon rate of 12 kg CO_2 per cubic meter of sawn lumber. Since the summary includes all processes from the time the logs arrive at the site to when the lumber is ready for transportation, no additional computation is needed. After the milling process, the lumber is transported to the treatment facility. The transportation of sawn lumber can utilize the previously introduced Equation [4].

Upon arrival at the treatment plant, the lumber is loaded into a vacuum pressure vessel where it will be dried and infused with preservatives. This pressurized chamber forces the preservatives deep into the lumber's cells. After the wood is removed from the vessel, it is placed on a drip pad for 24-48 hours to rid itself of excess preservatives. The timber is then reloaded on a freight truck and the treatment process is complete.

From an embodied carbon point of view, there are two main processes to consider within the pressure-treating process. Firstly, the contribution from the machinery used for the removal and loading of the lumber will need to be determined. The previously noted Equation [3] can be used to determine the carbon emitted during this step. The second process requiring computation is the vacuum pressure vessel. Although little standard information is available for the carbon emission of vacuum pressure vessels, an estimation can be calculated by assuming the vessel is powered by a natural gas boiler. This assumption is relevant given many vessels use steam or another form of gas to pressurize the tank. If this assumption is made, an embodied carbon rate can be analyzed from the boiler itself. Using a natural gas combustion publication from the EPA, a carbon dioxide emission rate of 1.92 kg/m^3 of natural gas can be collected. It is also important to note that carbon monoxide is released from this process as well, however this value (.001 kg/m^3) is very minimal compared to carbon dioxide and so it can be considered negligible in this determination. These two computations conclude the treatment plant's contribution to the collection of embodied carbon within timber structural systems. The next life cycle phase to consider is the lumber transportation to distribution companies. The embodied carbon computation for the post-treatment facility transportation is identical to the method used to evaluate transportation from the milling facility to the treatment plant.

Little additional carbon emission is created at the distribution company since the wood has already gone through its multitude of processes. The only consideration is the carbon emission related to unloading and reloading of material that may take place before the lumber reaches the construction site. This emittance can be determined using the previously stated Equation [3]. Once the wood is ready for transport to the construction site, the product phase (A1-A3, Table 1) has officially concluded, and the construction phase can begin.

Timber Construction Phase

The construction phase (A4-A5, Table 1) represents the emission from assembling the timber structure. This process begins with transporting the materials to the construction site. Once the members are on-site, machinery is used to cut, hoist, and piece together the structure. Connections for these members will not be included in this report but should be considered in a full-building analysis. Although most of the carbon emission stems from the larger machinery used for the project, employee transportation to and from the worksite adds a substantial amount of embodied carbon. It is important to accurately consider the number of trips used during the project due to the extensive time construction can take. Once the structure is fully erected, the construction phase is complete.

The first carbon-producing process in the construction phase is the transportation of the freight to the construction site. The previously stated Equation [4] can be used for this summary. Once the members are on-site, assembly of the superstructure can begin. Many forms of machinery are used in building timber structures. The equipment can typically be sectioned into fuel-burning and electric-powered machinery. Given the versatility of Equation [3], all fuel-powered machinery can use this equation to determine their carbon contribution. Like the process for electric vehicle use, embodied carbon for electric devices, such as battery-powered saws and drills, can be found by using the previously introduced Table [5]. This table lists the emissions for lithium-ion batteries, the most-used type of battery for handheld devices. Unlike fuel-powered tools, the emission rates of electric tools do not vary based on a load factor. The rate of carbon emission will be determined by dividing the summation of embodied carbon required to manufacture the item by the lifetime expectancy of each battery. Therefore, if a device is damaged prior to reaching its expected hours of usage, the carbon emission rate would be higher and vice versa.

The final carbon emitting process in the construction phase is the employee travel to and from the project site. This travel can include manual laborers, managers, engineers, etc. Table [2] and [3] can once again be used for this calculation. Transportation that could arguably be included is the employee travel to and from lunch breaks. This transportation will be excluded in the report due to the following. If the structure were to not be constructed, the employees may still choose to drive themselves elsewhere to eat. Since this emission can be considered as part of the personal life of the employee, it has been determined to leave this travel out of the embodied carbon contribution of the structure. After all elements of the structure are fastened together and the final trips to and from the construction site have concluded, the cradle to gate phases (A1-A5, Table 1) of the embodied carbon assessment are finished.

Timber In-Use Phase

Although most greenhouse gas emissions during the in-use phase (B1-B7, Table 1) of a building stem from operational carbon, there is also a process involving the embodied carbon of the structure known as material replacement. This process can greatly affect the carbon efficiency of a structure when comparing building materials. For example, timber is generally known for having a lower embodied carbon total at completion of construction than concrete. However, the replacement period of timber is short in comparison to concrete. Therefore, the selection of timber over other material choices could potentially net a higher carbon footprint after demolition if the timber elements are replaced more frequently.

With any timber structure, wood-rot is a great concern to the structural integrity of the building. Despite efforts to protect the wood with treatments and preservatives, it is not uncommon for moisture and insects to cause damage to timber members. If such damage occurs unchecked, over time, the structure will degrade and decompose to an unsafe state. Therefore, the replacement period of timber is typically a much shorter time when compared to other structural materials. Since many site-specific factors contribute to the replacement period of timber, a summarization of the embodied carbon after construction would be difficult to accurately forecast due to the variables involved. Therefore, the in-use phase (B1-B7, Table 1) of the embodied carbon assessment in this research will not be included in the results summary. Since this addition would be unknown until the replacement period arrives, the total embodied carbon of the structure would take many years to accurately assess in the field.

Concrete Product Phase

As examined for timber structural systems, concrete utilizes the same phases as previously discussed. Concrete's product phase (A1-A3, Table 1) begins with the collection and preparation of raw and required materials. Unlike timber, concrete is made of multiple material components which each have different methods of collection. Therefore, the product phase will be split into subcategories for each of these components. Those of which include the aggregate, cement, chemical admixtures, and reinforcing steel. Unlike the embodied carbon rates selected for timber processes, all carbon rates utilized for the concrete components already include modules A-1 and A-2. Therefore, the raw materials extraction and transportation to the manufacturing site have already been included and do not require additional calculation. After the needed materials are obtained, the emissions from the mixing process, formwork construction, and transportation of materials and personnel can be added to complete the sum of embodied carbon.

One of the first products needed in reinforced concrete is the aggregate. Aggregate is the granular material in concrete and typically takes up the largest portion of volume in the mix. Common examples of aggregate are crushed rock, gravel, and sand. Aggregate is classified based on its size. The two main size classifications for this material are course and fine aggregate. These classifications are represented in Table [6] as crushed rock, and sand/gravel respectively. This table is from a British geological survey published by the Natural Environment Research Council (NERC) and displays the average carbon rate of typical aggregate products. The rates show an embodied carbon total based on the tonnage of aggregate used. These values consider all processes needed to manufacture the aggregate, including transportation of personnel to and from the mining sites. The resulting rates of carbon dioxide are 4.28 (kg CO_2/metric ton) of sand/gravel aggregate and 4.32 (kg CO_2/metric ton) of crushed rock aggregate. For a typical concrete mix of 70% aggregate with a 4:6 ratio of sand/gravel to crushed rock, this equates to around 4.88 kg of CO_2 per cubic meter of concrete.

The next concrete material to obtain is the cement. The dry process to create cement starts with quarrying raw materials. The materials are then transported to a cement plant where they will be crushed and blended with other ingredients such as iron ore or fly ash. Afterwards, they are heated in a kiln up to 1500°C to disperse unwanted elements, ground up further, and finally mixed with gypsum and limestone. The wet process is like the dry process, except the materials are mixed

Table 6. Embodied Carbon of Typical Aggregate Products
(from nora.nerc.ac.uk)

Mineral Product	Carbon Dioxide Rate (kg/metric ton)
Sand and Gravel	4.28
Crushed Rock	4.32

with water prior to entering the kiln. The carbon emission of cement production has been figured by the Portland Cement Association (PCA). Their publication states the rate of embodied carbon consists of 0.9 (kg CO_2/kg cement). For a typical concrete mix of 15% cement, a resulting 203.3 kg of CO_2 is released per cubic meter of concrete.

Other carbon-emitting products used in concrete production are additives used to adjust mixes for weather conditions and ease of placement. There are many ways to alter concrete composition. Although many are used, this research will focus on two of the most utilized additives: air entraining mixtures and water reducers. The European Federation of Concrete Admixtures Associations (EFCA) has published tables listing the amount of carbon dioxide equivalents produced while manufacturing these products. To appropriately use these values, the total carbon emission must combine the processes in the product and construction phase to accurately include them in this report. These phases are displayed in Table [1] as module A-1 through A-5. This time-span accounts for the emissions from extraction of materials to assembly. Thus, yielding a value of 0.56 kg CO_2 eq./kg air entrainer and 1.64 kg CO_2 eq./kg plasticizer (water reducer). Although these rates may seem high at first glance, the relatively small volume of required admixture materials results in a minimal amount of embodied carbon when compared to the total composition of the concrete.

The final material needed for the construction of reinforced concrete is reinforcing steel. Unlike other materials that decompose quickly or undergo irreversible chemical processes, steel is highly recyclable. According to the American Institute of Steel Construction (AISC), 72% of reinforcing bars come from recycled steel. This prolongs the efficiency of the material, reducing its carbon rate. Since the bars can be thought of as hybrid materials of recycled and original steel, two carbon rates will need to be combined to account for the composition of the steel bars. The World Steel Association (WSA) lists an emissions value of 1.85 metric tons of CO_2 per ton of steel produced. When examining this source further, a breakdown is available including the amount of recycled steel present in this assumption. The report uses a weighted average of the Blast Furnace-Basic Oxygen Furnace (BF-BOF) method and the Electric Arc Furnace (EAF) method for their findings. The two methods have very different carbon emission rates. The BF-BOF method uses 13.8% recycled steel while the EAF method uses 105% recycled steel. This extra 5% is considered for the loss of material accumulated through this method. However, neither of these values directly correlate to the carbon rate needed for this analysis. As stated previously, 72% of reinforcing bars are recycled material. Since the emission rates from the sources provided consider many applications of steel production, an adjustment needs to be made before the value is ready to be used for reinforcing steel specifically. The publication source lists the carbon footprints of the two methods separately. Since the EAF method only uses recycled material, the carbon rate can be determined and plugged into the weighted average of the BF-BOF method to figure separate rates for recycled vs originally produced steel. The yielding values are .34 metric tons of CO_2 per metric ton of steel for recycled material and 2.25 metric tons of CO_2 per metric ton of originally produced steel. Using these values, a weighted rate of 875 kg of CO_2 per metric ton of reinforcing steel can be determined for reinforcing steel bars.

To contain the concrete during placement and while it cures, formwork is needed. Formwork is typically constructed with lumber or plywood and is easily reusable. Many sources consider formwork to have an infinite lifetime if maintained properly. Given this information, the carbon emission of the formwork will be neglected for this report.

The final carbon-emitting process in the product phase (A1-A3, Table 1) of concrete construction is the transportation of materials to and from the manufacturing locations, as well as the ready-mix locations where they wait to be distributed. The previously stated Equation [4] can be used for the carbon footprint of this travel. Once the materials have been delivered to the distributing companies, the construction phase can begin.

Concrete Construction Phase

The construction phase (A4-A5, Table 1) of a concrete structure does not largely vary from the construction of timber structures. Material transportation is needed to the site and many of the equipment used for timber erection is also used when constructing concrete structures. One of the largest differences between the two systems is the sum of worker transportation to and from the site. Since concrete is a denser material than timber, it typically requires a more labor-intensive construction process to encompass the work phases of forming, reinforcing, placing, and finishing. This increases the time required to erect the structure, leading to additional trips to the site by the workforce. The previously stated Table [2] and [3] can be used to figure the emission of this transportation. Concrete mixing trucks are responsible for transporting plastic (wet) concrete to the site. Although these vehicles are not typically thought of as freight trucks, the emissions factor listed in Equation [4] allows the embodied carbon to be figured accordingly. The methods for computing the carbon emission stemming from the material transportation, employee transportation, and equipment usage can be replicated from the timber construction phase. This concludes the construction phase (A4-A5, Table 1) for concrete structural systems.

Concrete In-Use Phase

Like timber, concrete structures do not contribute a large summation of embodied carbon after instillation. Replacement material is typically the only item to consider over the lifetime of the building until its demolition. Concrete does not rot like timber; however, concrete is very susceptible to cracking and may need maintenance over time for aesthetic, functional, or structural longevity. To determine an accurate summation of embodied carbon within the structural system, the frequency and extent of maintenance over the concrete's service life cannot be predicted. Therefore, the in-use phase (B1-B7, Table 1) of the embodied carbon assessment will remain unfinished until after the building is demolished.

Timber vs Concrete Comparisons

Despite their distinct visual differences, timber and concrete building systems have many things in common. Transportation of material is similar for both systems. The raw materials are typically carried by some sort of freight-hauling vehicle to a mill/plant where they are processed into the final usable forms and then transported to the construction site where it will be utilized. The transportation of workers to build the structure is also alike. Each crew traveling by some sort of fuel-burning or electric vehicle. Although many parts of the process are indistinguishable, they are still vital to the overall comparison due to the variances presented by each unique project. For example, transportation might use the same formula for carbon emissions, but the distance required to obtain the material could be drastically different depending on project location. Therefore, examining these variances will allow for meaningful comparisons for each structural material.

Despite many similarities, there are also multiple differences between the carbon emission of timber and concrete structural systems. One of the discrepancies is the material collection sector of the product phase. Lumber goes through many processes to be cut to the correct shape, dried and treated for durability but is not supplemented with many other products. Whereas concrete has many components with their own production processes that are eventually combined to form a cohesive material. As previously discussed, both materials are transported to some type of plant, mill or treatment facility. However, the processes taking place at each location are vastly different from one another, creating additional discrepancies between the two materials. Furthermore, the speed of construction can vary between these systems. Timber is a more lightweight material which typically allows for a faster erection time with less personnel needed on site. A lighter material also yields a smaller foundation substructure needed to support the super-structure. On the other hand, concrete's durability is more robust than timber. Concrete has been known to withstand events such as fire, severe weather, and other natural disasters, leading to less maintenance needed over the duration of its service life.

As described above, there are many similarities and discrepancies that must be considered in the cradle to gate stages of timber and concrete structural systems. Without specific project criteria, no material can be ensured as the most carbon-efficient system due to the numerous site-specific parameters previously discussed.

Sample Calculation

To provide an example of how this report could be utilized, a sample computation has been provided below. This example will compare the embodied carbon of a proposed building using a timber vs concrete structural system. All material and geological information have been assumed based on educated ratios deemed appropriate to represent a reasonable example. Connections and roof structures will be excluded from this example.

Sample Information

The fictional building used in this example is located on the Kansas State University campus in Manhattan, KS. The building is a single-story, 20,000 ft^2 building with no basement. All timber products in this example are harvested from the Daniel Boone National Forest in Kentucky. A local sawmill and treatment facility will be used before the material is transported to Mead Lumber in Manhattan, KS for distribution. The timber frame structure is composed of 2x4 members at 16" O.C. All concrete products are mixed and transported from Midwest Concrete Materials (MCM) in Manhattan, KS. The cement used in this process comes from the Central Plains Cement Company in Wichita, KS. All aggregates are sourced locally by MCM. Admixtures are from SIKA Manufacturing in Grandview, MO. The concrete frame structure is to be cast in place with removable formwork. A concrete compressive strength of 4000 psi is to be assumed. All reinforcing steel is transported from KC Steel Inc. in Kansas City, MO.

Vehicle Information:

The following vehicles will be used in the carbon summation of employee transportation.

→ (2) 2021 Ford F150 5.0L, V8, Gasoline, Tier 3, Bin 70, 19 mpg

→ 2018 Chevy Cruze 1.4L, V4, Gasoline, Tier 3, Bin 50, 33 mpg

→ 2016 Honda Pilot 3.5L, V6, Gasoline, Tier 2, Bin 5, 23 mpg

→ 2022 Ford F150 Lightning, Electric, 675kg battery, 0.49 kWh/mi

Timber Structural System

Lumber Volume Required for Construction: 10,500 ft^3, 300 m^3

→ .525 ft^3 lumber/ft^2 floor space

Timber Volume Required for Logging: 330 m^3

→ Assuming a 10% volume loss from timber to lumber processing.

Timber System's Foundation (slab on grade)

Concrete Volume: 100 m^3

Aggregate: 70% of Concrete Mix

→ Crushed Rock: 60%, 42 m^3, 67.3 metric tons using 1602 kg/m^3

→ Sand/Gravel: 40%, 28 m^3, 46.2 metric tons using 1650 kg/m^3

Cement: 15% of Concrete Mix

→ 15 m^3, 22,590 kg using 1506 kg/m^3

Additives: 0.5% of Concrete Mix

Air-Entrainer: 70mL/100kg of concrete = 168,000 mL

Total concrete weight = (100 m^3)*(2400 kg/m^3) = 240,000 kg

Specific Weight = 1.01, Density = .00101 kg/mL

Weight = .00101*168,000 = 169.7 kg

Plasticizer/Water Reducer: 150mL/100kg of concrete = 360,000 mL

Specific Weight = 1.14, Density = .00114 kg/mL

Weight = .00114*360,000 = 410.4 kg

Water: 14.5% of Concrete Mix

Reinforcing Steel: Assuming 2% of Concrete Volume = 2 m^3

Density = 7850 kg/m^3

Weight = 2*7850 = 15,700 kg = 15.7 metric tons

Concrete Structural System

Concrete Volume Required for Construction: 1000 m^3

→ .05 m^3 concrete/ft^2 floor space

Aggregate: 70% of Concrete Mix

→ Crushed Rock: 60%, 420 m^3, 672.8 metric tons using 1602 kg/m^3

→ Sand/Gravel: 40%, 280 m^3, 462.0 metric tons using 1650 kg/m^3

Cement: 15% of Concrete Mix

→ 150 m^3, 225,900 kg using 1506 kg/m^3

Additives: 0.5% of Concrete Mix

Air-Entrainer: 70mL/100kg of concrete = 1,680,000 mL

Total concrete weight = (1000 m^3)*(2400 kg/m^3) = 2,400,000 kg

Specific Weight = 1.01, Density = .00101 kg/mL

Weight = .00101*1,680,000 = 1696.8 kg

Plasticizer/Water Reducer: 150mL/100kg of concrete = 3,600,000 mL

Specific Weight = 1.14, Density = .00114 kg/mL

Weight = .00114*3,600,000 = 4104 kg

Water: 14.5% of Concrete Mix

Reinforcing Steel: Assuming 2% of Concrete Volume = 20 m^3

Density = 7850 kg/m^3

Weight = 20*7850 = 157,000 kg = 157.0 metric tons

Concrete System's Foundation (slab on grade)

Concrete Volume: 120 m^3

Aggregate: 70% of Concrete Mix

→ Crushed Rock: 60%, 50.4 m^3, 80.7 metric tons using 1602 kg/m^3

→ Sand/Gravel: 40%, 33.6 m^3, 55.4 metric tons using 1650 kg/m^3

Cement: 15% of Concrete Mix

→ 18 m^3, 27,108 kg using 1506 kg/m^3

Additives: 0.5% of Concrete Mix

Air-Entrainer: 70mL/100kg of concrete = 201,600 mL

Total concrete weight = (120 m^3)*(2400 kg/m^3) = 288,000 kg

Specific Weight = 1.01, Density = .00101 kg/mL

Weight = .00101*201,600 = 203.6 kg

Plasticizer/Water Reducer: 150mL/100kg of concrete = 432,000 mL

Specific Weight = 1.14, Density = .00114 kg/mL

Weight = .00114*432,000 = 492.5 kg

Water: 14.5% of Concrete Mix

Reinforcing Steel: Assuming 2% of Concrete Volume = 2.4 m^3

Density = 7850 kg/m^3

Weight = 2.4*7850 = 18,840 kg = 18.84 metric tons

Assumed Timber Distances

50 miles: Logging Equipment to Logging Site

30 miles: Average Worker Transportation to Logging Site

50 miles: Logging Site to Sawmill

50 miles: Sawmill to Lumber Treatment Facility

760 miles: Lumber Treatment Facility to Lumber Distribution Facility

3 miles: Lumber Distribution Facility to Construction Site

Assumed Concrete Distances

140 miles: Cement Manufacturing Location to Concrete Ready-Mix Batch Plant Location

135 miles: Admixture Manufacturing Location to Concrete Ready-Mix Location

4 miles: Concrete Mixing Location to Construction Site

125 miles: Reinforcing Steel Distribution Location to Construction Site

Assumed Construction Distances

30 miles: Construction Equipment to Construction Site

20 miles: Average Worker Transportation to Construction Site

Assumed Timber Equipment/Material Transportation Distances

200 miles: Logging Equipment to and from Logging Site

→ (2 trips)*(100 miles) = 200 miles

1400 miles: Timber Transportation to Sawmill

→ (330 m^3)/(12 m^3/load) = 28 loads required

→ (28 trips)*(50 miles) = 1400 miles

1400 miles: Unloaded Timber Transportation from Sawmill

1250 miles: Lumber Transportation to Treatment Facility

→ (300 m^3)/(12 m^3/load) = 25 loads required

→ (25 trips)*(50 miles) = 1250 miles

1250 miles: Unloaded Lumber Transportation from Treatment Facility

19,000 miles: Lumber Transportation to Lumber Distribution Facility

→ (25 trips)*(760 miles) = 19,000 miles

19,000 miles: Unloaded Lumber Transportation from Lumber Distribution Facility

75 miles: Lumber Transportation to Construction Site

→ (25 trips)*(3 miles) = 75 miles

75 miles: Unloaded Lumber Transportation from Construction Site

280 miles: Cement Transportation to Concrete Ready-Mix Location

→ (15 m^3)/(8 m^3/load) = 2 loads required

→ (2 trips)*(140 miles) = 280 miles

280 miles: Unloaded Cement Transportation from Concrete Ready-Mix Location

135 miles: Admixture Transportation to Concrete Ready-Mix Location

→ 1 trip required

135 miles: Unloaded Admixture Transportation from Concrete Ready-Mix Location

52 miles: Concrete Transportation to Construction Site

→ (100 m^3)/(8 m^3/load) = 13 loads required

→ (13 trips)*(4 miles) = 52 miles

52 miles: Unloaded Concrete Transportation from Construction Site

250 miles: Reinforcing Steel Transportation to Construction Site

→ (15.7 metric tons)/(14 metric tons/load) = 2 loads required

→ (2 trips)*(125 miles) = 250 miles

250 miles: Unloaded Reinforcing Steel Transportation from Construction Site

Assumed Concrete Equipment/Material Transportation Distances

2940 miles: Cement Transportation to Concrete Ready-Mix Location

→ (168 m^3)/(8 m^3/load) = 21 loads required

→ (21 trips)*(140 miles) = 2940 miles

2940 miles: Unloaded Cement Transportation from Concrete Ready-Mix Location

135 miles: Admixture Transportation to Concrete Ready-Mix Location

→ 1 trip required

135 miles: Unloaded Admixture Transportation from Concrete Ready-Mix Location

560 miles: Concrete Transportation to Construction Site

→ (1120 m^3)/(8 m^3/load) = 140 loads required

→ (140 trips)*(4 miles) = 560 miles

560 miles: Unloaded Concrete Transportation from Construction Site

1625 miles: Reinforcing Steel Transportation to Construction Site

→ (175.8 metric tons)/(14 metric tons/load) = 13 loads required

→ (13 trips)*(125 miles) = 1625 miles

1625 miles: Unloaded Reinforcing Steel Transportation from Construction Site

Assumed Construction Equipment Transportation Distances

600 miles: Construction Equipment to and from Construction Site

→ (10 trips)*(60 miles) = 600 miles

Employee Transportation Distances

3000 miles: Logging

→ Assume an average of 5 people on site. Assume an average logging rate of 3 loads a day with 28 loads total, resulting in a 10-day logging period. Assuming the average person drives 30 miles to and from the site once a day = 10 days*5 people*60 miles = 3000 miles total. These miles have been split up into 5 vehicles in the example. Equaling 600 miles for each vehicle.

219,000 miles: Timber Construction

→ Assume an 8-month structural construction period with an average of 15 people on site. Assuming the average person drives 20 miles to and from the site once a day = 240 days*15 people*40 miles = 144,000 miles total. These miles have been split up into 4 vehicle types in the example for simplicity. Equaling 36,000 miles for each vehicle type.

306,000 miles: Concrete Construction

→ Assume a 10-month structural construction period with an average of 18 people on site. Assuming the average person drives 20 miles to and from the site once a day = 300 days*18 people*40 miles = 216,000 miles total. These miles have been split up into 4 vehicle types in the example for simplicity. Equaling 54,000 miles for each vehicle type.

Transportation Loading

Lumber/Logging Truck: 1 metric ton

Logging Load: 7.1 m^3*1600 kg/m^3 = 11,360 kg/load = 11.36 metric tons/load

Cement/Concrete Truck: 10 metric tons

Cement Load: 8 m^3*1440 kg/m^3 = 11,520 kg/load = 11.52 metric tons/load

Concrete Load: 8 m^3*2400 kg/m^3 = 19,200 kg/load = 19.2 metric tons/load

Reinforcing Steel Truck: 10 metric tons

Reinforcing Steel Load: 14 metric tons/load

Admixture Truck: 5 metric tons

Truck Hauling Large Equipment: 25 metric tons

Equipment Operational Activity

80 hours: Logging

→ (10 days)*(8 hrs/day) = 80 hours

40 hours: Loading/Unloading Lumber at Treatment Facility

→ Assumed ½ the time of logging.

40 hours: Loading/Unloading Lumber at Distribution Facility

240 hours: Earth-Moving Equipment (Timber System)

→ (30 days)*(8 hrs/day) = 240 hours

1680 hours: Material Handling Equipment (Timber System)

→ (210 days)*(8 hrs/day) = 1680 hours

1680 hours: Hand-Held Equipment (Timber System)

→ (210 days)*(8 hrs/day) = 1680 hours

240 hours: Earth-Moving Equipment (Concrete System)

→ (30 days)*(8 hrs/day) = 240 hours

2160 hours: Material Handling Equipment (Concrete System)

→ (270 days)*(8 hrs/day) = 2160 hours

2160 hours: Hand-Held Equipment (Concrete System)

→ (270 days)*(8 hrs/day) = 2160 hours

Utilized Equipment

Chainsaw:

→ Power: 3.5 hp

→ Economy: 4 hr/gal

→ Carbon Monoxide Emission Factor: 350 g/hp-hr

(2) Tractors:

→ Power: 60 hp

→ Economy: 15 hp-hr/gal

→ Carbon Monoxide Emission Factor: 25 g/hp-hr

Loader:

→ Power: 168 hp

→ Economy: 15 hp-hr/gal

→ Carbon Monoxide Emission Factor: 25 g/hp-hr

Natural Gas Boiler:

→ Treatment Process Usage: 18 m^3 natural gas

Earth-Moving Equipment (Excavator): Diesel

→ Power: 300 hp

→ Economy: 15 hp-hr/gal

→ Carbon Monoxide Emission Factor: 25 g/hp-hr

Material Handling Equipment (All-terrain forklift): Gasoline

→ Power: 250 hp

→ Economy: 15 hp-hr/gal

→ Carbon Monoxide Emission Factor: 350 g/hp-hr

Hand-Held Equipment: Gasoline

→ Power: 3 hp

→ Economy: 4 hr/gal

→ Carbon Monoxide Emission Factor: 350 g/hp-hr

*No electric construction equipment for example.

Sample Calculation Results

Table 7. Sample Calculation Results Summary (kg C = kilograms of carbon)

Phase	Process	Timber System (kg C)	Concrete System (kg C)
Product	Worker Transportation	308	--
Product	Equipment Transportation	243	--
Product	Timber Transportation	14,057	--
Product	Concrete Transportation	498	4611
Product	Logging Equipment	1375	--
Product	Milling Process	983	--
Product	Treatment Facility	392	--
Product	Distribution Facility	382	--
Product	Aggregate	133	1493
Product	Cement	5550	62,164
Product	Additives	210	2348
Product	Reinforcing Steel	3750	42,004
Construction	Worker Transportation	13,866	31,998
Construction	Equipment Transportation	729	729
Construction	Lumber Transportation	49	--
Construction	Concrete Transportation	512	3752
Construction	Construction Equipment	30,110	37,382
	(A1-A3) Product Phase Total:	27,881	112,621
	(A4-A5) Construction Phase Total:	45,266	73,861
	Total:	73,146	186,482

Table 8. Comparison – Report v. Embodied Carbon Order of Magnitude (SE 2050)

	Timber System (kg C)	Concrete System (kg C)
Assessment of Embodied Carbon in Timber and Concrete Building Systems (This Report)	73,146	186,482
Embodied Carbon Order of Magnitude (SE 2050)	24,596	141,652
Difference	48,550	44,830

The results of this example shown in Table [7] yielded the timber system as the more carbon efficient structural material for this building. The estimation resulted in higher embodied carbon totals than the ECOM estimating tool from the Structural Engineering Institute. This is expected since the ECOM estimating tool only considers the structural components of the project. Any process outside of this, such as employee and material transportation, is not considered in the ECOM framework. Although SEI's estimating tool is user friendly and provides a baseline estimate, the differences shown in Table [8] indicate there are many other project-specific factors that influence the embodied carbon of a project.

The results summary in Table [7] represents one of the main benefits of this report. When examining the sample building in a process-specific manner, areas of larger carbon emission can be isolated and recognized. For example, although the timber system looks decently balanced, there is quite a bit of embodied carbon stemming from timber transportation. A potential reduction in this area could be achieved by choosing a closer harvesting location for the raw materials. In the concrete system, a large portion of carbon emission is due to cement production. A possible reduction strategy for the cement could include using alternative mix designs. The reinforcing steel also appears to contribute a large amount of embodied carbon in the concrete system. A way to decrease the emission of the steel could be to increase the ratio of recycled content or decrease the overall reinforcing materials needed by reducing span lengths within the building. These are examples of how this report could be utilized as additional guidance for designers in the carbon reduction efforts of a building superstructure.

Discussion

Reduction Techniques

Some of the most applicable steps currently taken for carbon neutrality are reduction techniques. There are several general techniques involving timber and concrete. The most common strategy is material efficiency. This can include basic principles such as reducing construction waste and preventing overdesign. However, there are more complex ideas like topology optimization. This method is based on the idea of determining the most optimal orientation and spacing of structural members for given loads and dimensional requirements.

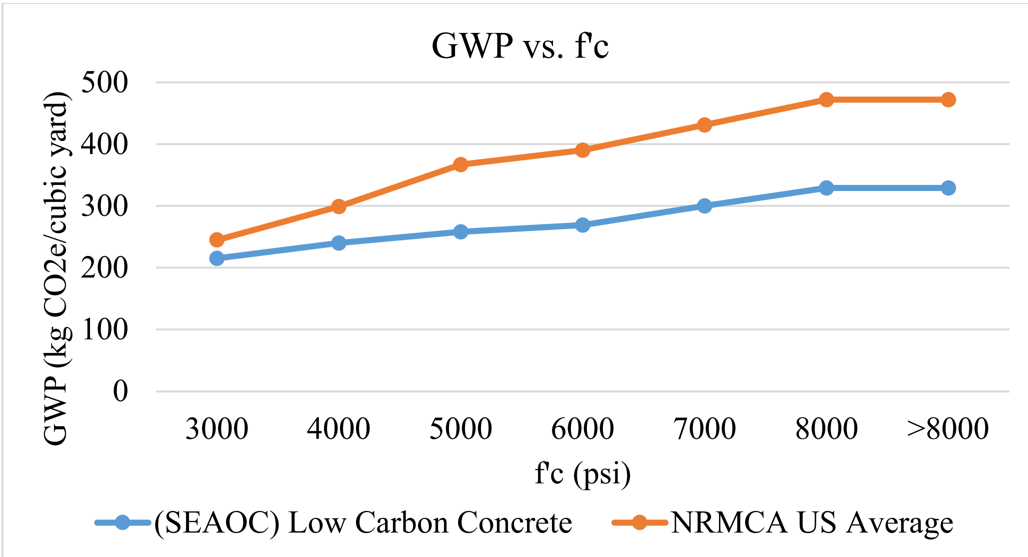
When determining timber specific reduction strategies, a few new options have recently arisen. One example of this is bioengineering for higher strengths of wood. This eventually leads to less material needed for the project. Another idea is optimized framing commonly known as value engineering. This idea includes strategies such as increased stud spacing, singular top plates, and minimizing the number of studs at corners. Although some of these reductions result in a decrease of strength, the reason many of these examples are not implemented is due to common industry practice rather than actual strength requirements.

Concrete has a large potential for carbon reduction. Some specific strategies are utilizing voided slab systems or post-tensioned slabs to reduce the volume required. Another technique is similar to value engineering described for timber structures. This would involve using thinner slabs on grade and foundation walls. One way to obtain a reduction in this manner could be implementing frost-protected shallow foundations to reduce depth. Beyond material volume reduction, one of the most effective ways to reduce the carbon emission in concrete is lowering the proportion of cement in the mix. One way of accomplishing this is by specifying a 56- or 112-day compressive strength rather than the standard 28 day. However, increasing the cure time for the concrete mix could potentially delay other concrete activities of the project. Additionally, supplementary cementitious materials (SCMs) could be used in place of cement. Examples of these materials are fly ash or slag which have a much lower global emissions rate. To visualize this difference, Figure [2] displays a study by the Structural Engineers Association of California (SEAOC) Sustainable Design Committee. The study compared the global warming potential of varying concrete mix designs over a 5-year period. The two lines display the average emission rates of standard U.S. mix designs vs alternative compositions with the same compressive strength. The results show the drastic impact a supplemented mix design can make on global emission rates. For example, if the fictional building above was to use an alternative low-carbon mix design (142.4 $kgCO_2/yd^3$) for the concrete system, the carbon footprint would decrease by 22,139 kg of carbon. This equates to an 11.9% reduction in the entire superstructure. One of the newest methods of reducing carbon within concrete production is in the production process of cement. Since cement comprises the largest proportion of carbon in concrete, limiting this element can have a significant effect. Using Carbon Capture, Utilization, and Storage (CCUS) techniques, carbon emissions can be captured directly from the cement plant and reused for production processes leading to a smaller excretion of harmful greenhouse gases globally.

Reduction strategies are gaining more traction as the push for a carbon-neutral built-environment is growing around the world. With advancements in technology and improvements in concrete production processes, the associated carbon reductions will serve to support a much greater impact over time. Eventually these efforts, combined with carbon-reversing procedures, could help pave the way for achieving neutral embodied carbon structural systems.

Figure 2. GWP of Concrete Mixes Relative to Strength

(from wordpress.com)



Conclusion

The building industry has a long way to go before reaching carbon neutrality. The numerous processes required for building design leads to a substantial amount of carbon emission each year. Although efforts to reduce emission rates and create more optimal products have improved carbon efficiency over the years, additional techniques will need to be introduced to reverse decades of negative impacts. One of the newest technologies for accomplishing this is the utilization and manipulation of carbon sequestration. Carbon sequestration opens new possibilities for not only reducing, but also counteracting carbon emission on a global scale. With additional research and implementation, this method has potential to be a leading tool for reaching SE 2050 deadlines.

The sample building in this report resulted in 73,294 kgC for the timber structure and 186,482 kgC for the concrete structure. To put these numbers into perspective, the average yearly embodied carbon accumulation of a 2021 Ford F-150 pickup truck (5.0L V8 driven 13,000 mi/yr) is 1670 kgC. Therefore, the embodied carbon footprint of the timber and concrete structures in the cradle to gate phases (A1-A5, Table 1) is equivalent to the yearly miles of 43.9 and 111.7 F150s respectively. The results summary in Table [7] yielded timber as the more efficient structural material for this building. Although the results were very distinct, there is still some possibility for concrete to yield a more carbon efficient design depending on project location, available materials, reduction strategies employed, and other project-specific criteria. Due to this possibility and external factors of the project, it cannot be assumed that timber will always be the more eco-friendly structural material.

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Appendix

Sample Results

Assessment of Embodied Carbon in Timber and Concrete Building Systems

This tool serves to provide a detailed breakdown of embodied carbon within timber and concrete building systems. The tool allows users to identify which areas in their design are the least carbon efficient to aid in carbon reduction efforts.

Inputs:
Results:

Timber

Product Phase

Worker Transportation

Fuel Powered

Vehicle I: 2021 F150 5.0L, V8, Gasoline

Tier:	3	CO Emission Rate (g/mi)		Distance Traveled (mi)
Bin:	70	1.7		600
CO Emissions (kg):	1.02	Fuel Type		Fuel Burned (gallons)
CO_2 Emissions (kg):	280.64211	Gasoline		31.57895

Vehicle II: 2021 F150 5.0L, V8, Gasoline

Tier:	3	CO Emission Rate (g/mi)		Distance Traveled (mi)
Bin:	70	1.7		600
CO Emissions (kg):	1.02	Fuel Type		Fuel Burned (gallons)
CO_2 Emissions (kg):	280.64211	Gasoline		31.57895

Vehicle III: 2018 Chevy Cruze 1.4L, V4, Gasoline

Tier:	3	CO Emission Rate (g/mi)		Distance Traveled (mi)
Bin:	70	1.7		600
CO Emissions (kg):	1.02	Fuel Type		Fuel Burned (gallons)
CO_2 Emissions (kg):	161.58182	Gasoline		18.18182

Vehicle IV: 2016 Honda Pilot, 3.5L, V6, Gasoline

Tier:	2	CO Emission Rate (g/mi)		Distance Traveled (mi)
Bin:	5	4.2		600
CO Emissions (kg):	2.52	Fuel Type		Fuel Burned (gallons)
CO_2 Emissions (kg):	231.83478	Gasoline		26.08696

Electric

Vehicle I: 2022 F150 Lightning

Battery Type	CO Emission Rate (g/kg)	CO_2 Emission Rate (kg/kg)
Lithium-Ion	3	12.5

Battery Size (kg)	Life Expectancy of Battery (mi)	Economy (kWh/mi)
675	100000	0.49

CO Emissions (kg):	0.01215	Distance Traveled (mi)
CO_2 Emissions (kg):	165.285	600

Logging Equipment

Equipment I: Gasoline Chainsaw

Power (hp)	Load Factor	Activity (hrs)
3.5	0.7	80

CO Emissions (kg):	68.6	CO Emissions Factor (g/hp-hr)	350
CO_2 Emissions (kg):	124.418	Fuel Type: Gasoline	Fuel Burned (gallons): 14

Equipment II: (2) Tractors

Power (hp)	Load Factor	Activity (hrs)
60	0.33	160

CO Emissions (kg):	79.2	CO Emissions Factor (g/hp-hr)	25
CO_2 Emissions (kg):	1876.9344	Fuel Type: Gasoline	Fuel Burned (gallons): 211.2

Equipment III: Loader

Power (hp)	Load Factor	Activity (hrs)
168	0.33	80

CO Emissions (kg):	110.88	CO Emissions Factor (g/hp-hr)	25
CO_2 Emissions (kg):	2627.7082	Fuel Type: Gasoline	Fuel Burned (gallons): 295.68

Timber/Equipment Transportation

Trip Description: Unloaded timber transportation to logging site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
1	1400	178

CO_2 Emissions (kg): 249.2

Trip Description: Fully loaded timber transportation to sawmill.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
12.36	1400	178

CO_2 Emissions (kg): 3080.112

Trip Description: Large equipment transportation to and from logging site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
25	200	178

CO_2 Emissions (kg): 890

Trip Description: Fully loaded lumber transportation to treatment facility and distribution company.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
12.36	20250	178

CO_2 Emissions (kg): 44551.62

Trip Description: Unloaded lumber transportation from treatment facility and distribution company.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
1	20250	178

CO_2 Emissions (kg): 3604.5

Foundation Material Transportation

Trip Description: Fully loaded cement transportation to ready-mix location.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
21.52	280	178

CO_2 Emissions (kg): 1072.5568

Trip Description: Unloaded cement transportation from ready-mix location.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
10	280	178

CO_2 Emissions (kg): 498.4

Trip Description: Fully loaded admixture transportation to ready-mix location.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
5.58	135	178

CO_2 Emissions (kg): 134.0874

Trip Description: Unloaded admixture transportation from ready-mix location.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
5	135	178

CO_2 Emissions (kg): 120.15

Milling Process

Sawn Lumber Volume (m^3)	CO_2 Emissions Factor (kg/m^3)
300	12

CO_2 Emissions (kg): 3600

Treatment Facility

Equipment I: Loader

Power (hp)	Load Factor	Activity (hrs)
168	0.33	40

CO Emissions (kg): 55.44

CO Emissions Factor (g/hp-hr): 25

CO_2 Emissions (kg): 1313.8541

Fuel Type	Fuel Burned (gallons)
Gasoline	147.84

Natural Gas Volume (m^3)	CO_2 Emissions Factor (kg/m^3)
18	1.92

CO_2 Emissions (kg): 34.56

Distribution Facility

Equipment I: Loader

Power (hp)	Load Factor	Activity (hrs)
168	0.33	40

CO Emissions (kg): 55.44

CO Emissions Factor (g/hp-hr): 25

CO_2 Emissions (kg): 1313.8541

Fuel Type	Fuel Burned (gallons)
Gasoline	147.84

Concrete Foundation

Aggregate

Crushed Rock Weight (metric ton): 67.3

Sand/Gravel Weight (metric ton): 46.2

CO_2 Emissions Factor (kg/metric ton): 4.32

CO_2 Emissions Factor (kg/metric ton): 4.28

CO_2 Emissions (kg): 488.472

Cement

Cement Weight (kg): 22590

CO_2 Emissions Factor (kg/kg): 0.9

CO_2 Emissions (kg): 20331

Additives

Air Entrainer Weight (kg): 169.7

Plasticizer Weight (kg): 410.4

CO_2 Emissions Factor (kg/kg): 0.56

CO_2 Emissions Factor (kg/kg): 1.64

CO_2 Emissions (kg): 768.088

Reinforcing Steel

Reinforcing Steel Weight (metric ton): 15.7

CO_2 Emissions Factor (kg/metric ton): 875

CO_2 Emissions (kg): 13737.5

Timber

Construction Phase

Worker Transportation

Fuel Powered

Vehicle Type I: 2021 F150 5.0L, V8, Gasoline

Tier:	3	CO Emission Rate (g/mi)	Distance Traveled (mi)
Bin:	70	1.7	36000
CO Emissions (kg):	61.2	Fuel Type	Fuel Burned (gallons)
CO_2 Emissions (kg):	16838.526	Gasoline	1894.737

Vehicle Type II: 2018 Chevy Cruze 1.4L, V4, Gasoline

Tier:	3	CO Emission Rate (g/mi)	Distance Traveled (mi)
Bin:	70	1.7	36000
CO Emissions (kg):	61.2	Fuel Type	Fuel Burned (gallons)
CO_2 Emissions (kg):	9694.9091	Gasoline	1090.909

Vehicle Type III: 2016 Honda Pilot, 3.5L, V6, Gasoline

Tier:	2	CO Emission Rate (g/mi)	Distance Traveled (mi)
Bin:	5	4.2	36000
CO Emissions (kg):	151.2	Fuel Type	Fuel Burned (gallons)
CO_2 Emissions (kg):	13910.087	Gasoline	1565.217

Electric

Vehicle Type I: 2022 F150 Lightning

Battery Type	CO Emission Rate (g/kg)	CO_2 Emission Rate (kg/kg)
Lithium-Ion	3	12.5

Battery Size (kg)	Life Expectancy of Battery (mi)	Economy (kWh/mi)
675	100000	0.49

CO Emissions (kg):	0.729	Distance Traveled (mi)
CO_2 Emissions (kg):	9917.1	36000

Lumber/Equipment Transportation

Trip Description: Large equipment transportation to and from construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
25	600	178

CO_2 Emissions (kg): 2670

Trip Description: Fully loaded lumber transportation to construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
12.36	75	178

CO_2 Emissions (kg): 165.006

Trip Description: Unloaded lumber transportation from construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
1	75	178

CO_2 Emissions (kg): 13.35

Trip Description: Fully loaded concrete transportation to construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
29.2	52	178

CO_2 Emissions (kg): 270.2752

Trip Description: Unloaded concrete transportation from construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
10	52	178

CO_2 Emissions (kg): 92.56

Trip Description: Fully loaded reinforcing steel transportation to construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
24	250	178

CO_2 Emissions (kg):	1068

Trip Description: Unloaded reinforcing steel transportation from construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
10	250	178

CO_2 Emissions (kg):	445

Construction Equipment

Fuel Powered

Equipment I: Earth-Moving Equipment

Power (hp)	Load Factor	Activity (hrs)
300	0.33	240

CO Emissions (kg): 594

CO Emissions Factor (g/hp-hr): 25

CO_2 Emissions (kg): 16125.12

Fuel Type: Diesel

Fuel Burned (gallons): 1584

Equipment II: Material Handling Equipment

Power (hp)	Load Factor	Activity (hrs)
250	0.33	1680

CO Emissions (kg): 3465

CO Emissions Factor (g/hp-hr): 25

CO_2 Emissions (kg): 82115.88

Fuel Type: Gasoline

Fuel Burned (gallons): 9240

Equipment III: Hand-Held Equipment

Power (hp)	Load Factor	Activity (hrs)
3	0.7	1680

CO Emissions (kg): 1234.8

CO Emissions Factor (g/hp-hr): 350

CO_2 Emissions (kg): 3732.54

Fuel Type: Gasoline

Fuel Burned (gallons): 420

Concrete

Product Phase

Aggregate

Crushed Rock Weight (metric ton)	Sand/Gravel Weight (metric ton)
672.8	462
CO_2 Emissions Factor (kg/metric ton)	CO_2 Emissions Factor (kg/metric ton)
4.32	4.28

CO_2 Emissions (kg): 4883.856

Cement

Cement Weight (kg)	CO_2 Emissions Factor (kg/kg)
225900	0.9

CO_2 Emissions (kg): 203310

Additives

Air Entrainer Weight (kg)	Plasticizer Weight (kg)
1696.8	4104
CO_2 Emissions Factor (kg/kg)	CO_2 Emissions Factor (kg/kg)
0.56	1.64

CO_2 Emissions (kg): 7680.768

Reinforcing Steel

Reinforcing Steel Weight (metric ton)	CO_2 Emissions Factor (kg/metric ton)
157	875

CO_2 Emissions (kg): 137375

Concrete Foundation

Aggregate

Crushed Rock Weight (metric ton)	Sand/Gravel Weight (metric ton)
80.7	55.4
CO_2 Emissions Factor (kg/metric ton)	CO_2 Emissions Factor (kg/metric ton)
4.32	4.28

CO_2 Emissions (kg): 585.736

Cement

Cement Weight (kg)	CO_2 Emissions Factor (kg/kg)
27108	0.9

CO_2 Emissions (kg): 24397.2

Additives

Air Entrainer Weight (kg)	Plasticizer Weight (kg)
203.6	492.5
CO_2 Emissions Factor (kg/kg)	CO_2 Emissions Factor (kg/kg)
0.56	1.64

CO_2 Emissions (kg): 921.716

Reinforcing Steel

Reinforcing Steel Weight (metric ton)	CO_2 Emissions Factor (kg/metric ton)
18.84	875

CO_2 Emissions (kg): 16485

Material Transportation

Trip Description: Fully loaded cement transportation to ready-mix location.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
21.52	2940	178

CO_2 Emissions (kg): 11261.846

Trip Description: Unloaded cement transportation from ready-mix location.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
10	2940	178

CO_2 Emissions (kg): 5233.2

Trip Description: Fully loaded admixture transportation to ready-mix location.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
11.5	135	178

CO_2 Emissions (kg): 276.345

Trip Description: Unloaded admixture transportation from ready-mix location.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
5	135	178

CO_2 Emissions (kg): 120.15

Concrete

Construction Phase

Worker Transportation

Fuel Powered

Vehicle Type I: 2021 F150 5.0L, V8, Gasoline

Tier:	3	CO Emission Rate (g/mi)		Distance Traveled (mi)
Bin:	70	1.7		54000
CO Emissions (kg):	91.8	Fuel Type		Fuel Burned (gallons)
CO_2 Emissions (kg):	25257.789	Gasoline		2842.105

Vehicle Type II: 2018 Chevy Cruze 1.4L, V4, Gasoline

Tier:	3	CO Emission Rate (g/mi)		Distance Traveled (mi)
Bin:	70	1.7		54000
CO Emissions (kg):	91.8	Fuel Type		Fuel Burned (gallons)
CO_2 Emissions (kg):	14542.364	Gasoline		1636.364

Vehicle Type III: 2016 Honda Pilot, 3.5L, V6, Gasoline

Tier:	2	CO Emission Rate (g/mi)		Distance Traveled (mi)
Bin:	5	4.2		54000
CO Emissions (kg):	226.8	Fuel Type		Fuel Burned (gallons)
CO_2 Emissions (kg):	20865.13	Gasoline		2347.826

Electric

Vehicle Type I: 2022 F150 Lightning

Battery Type	CO Emission Rate (g/kg)	CO_2 Emission Rate (kg/kg)
Lithium-Ion	3	12.5

Battery Size (kg)	Life Expectancy of Battery (mi)	Economy (kWh/mi)
675	10000	0.49

		Distance Traveled (mi)
CO Emissions (kg):	10.935	
CO_2 Emissions (kg):	55881.9	54000

Concrete/Equipment Transportation

Trip Description: Large equipment transportation to and from construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
25	600	178

CO_2 Emissions (kg): 2670

Trip Description: Fully loaded concrete transportation to construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
29.2	560	178

CO_2 Emissions (kg): 2910.656

Trip Description: Unloaded concrete transportation from construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
10	560	178

CO_2 Emissions (kg): 996.8

Trip Description: Fully loaded reinforcing steel transportation to construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
24	1625	178

CO_2 Emissions (kg): 6942

Trip Description: Unloaded reinforcing steel transportation from construction site.

Shipment Weight (metric ton)	Distance Traveled (mi)	CO_2 Emissions Factor (g/ton-mi)
10	1625	178

CO_2 Emissions (kg): 2892.5

Construction Equipment

Fuel Powered

Equipment I: Earth-Moving Equipment

Power (hp)	Load Factor	Activity (hrs)
300	0.33	240

CO Emissions (kg): 594

CO Emissions Factor (g/hp-hr): 25

CO_2 Emissions (kg): 16125.12

Fuel Type: Diesel

Fuel Burned (gallons): 1584

Equipment II: Material Handling Equipment

Power (hp)	Load Factor	Activity (hrs)
250	0.33	2160

CO Emissions (kg): 4455

CO Emissions Factor (g/hp-hr): 25

CO_2 Emissions (kg): 105577.56

Fuel Type: Gasoline

Fuel Burned (gallons): 11880

Equipment III: Hand-Held Equipment

Power (hp)	Load Factor	Activity (hrs)
3	0.7	2160

CO Emissions (kg): 1587.6

CO Emissions Factor (g/hp-hr): 350

CO_2 Emissions (kg): 4798.98

Fuel Type: Gasoline

Fuel Burned (gallons): 540

Results Summary

	Timber System	Concrete System
Carbon Monoxide Total (kg):	5943.3	7057.9
Carbon Dioxide Total (kg):	258595.4	671991.6
Carbon Total (kg):	73146.2	186481.6