Value-Based Conceptual Modeling of Costs and Embodied Carbon for Building Structural Systems: Mass Timber Perspective

Matthew Wiggins

A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Science in Construction Management

University of Washington

2021

Committee:

Hyun Woo Lee

Tomás Méndez Echenagucia

Program Authorized to Offer Degree:

Construction Management

University of Washington

Abstract

Value-Based Conceptual Modeling of Costs and Embodied Carbon for Building Structural Systems: Mass Timber Perspective

Matthew Wiggins

Chair of the Supervisory Committee:

Hyun Woo Lee

Department of Construction Management

Construction product manufacturing is a major contributor to the global climate change through its carbon emissions, known as embodied carbon (EC). In response, previous studies have found that utilizing a structural system of mass timber and cross laminated timber panels (CLT) can contribute to reduction of EC in the construction industry, when compared to other conventional structural systems. However, a major barrier that prevents the use of mass timber CLT is its higher cost than other available alternatives. In other words, project stakeholders that wish to reduce EC in their projects must justify the extra expense of selecting mass timber CLT. One method to achieve this justification is to demonstrate the value of such a decision. In that, quantifications of costs and reduced EC are needed to show the value by answering how much EC is reduced and how much does it cost. However, there is a dearth of studies aimed to develop an efficient framework to support the quantifications for value determination. The current practices require a significant amount of time and resources, which can cause project stakeholders to forgo the effort. To fill this knowledge gap, the objective of this project is to develop a new method, called the construction carbon reduction value model (CCRVM), which aims to improve the accessibility of structural system EC and construction cost data by streamlining the process of quantification and value determination. This is accomplished by automating the quantification steps and visualization of the data. To test the validity and usability of the CCRVM, a case study was performed to compare the costs and EC of four separate structural system alternatives based on a new university classroom building. Through the case study, the CCRVM proved to be an efficient and effective way of quantifying and comparing the costs and EC of the chosen alternatives. The case study findings show that structural alternatives that utilized mass timber CLT resulted in a percentage increase in construction costs but a much larger percentage reduction in EC. The CCRVM is expected to be an asset to project stakeholders that wish to lower EC by selecting mass timber CLT for their structural system. In addition to this it contributes a framework that can be used to test the EC and cost of other construction materials as well.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

ACKNOWLEDGEMENTS

I would first like to thank Dr. Hyun Woo Lee. This study would not be possible without your knowledge, guidance, and encouragement. I could not have asked for better mentor throughout this journey. Special thanks are also due to Dr. Tomás Mendez Echenagucia, who's thoughtful review and comments were essential in making this study something I am very proud of.

Most importantly, to my wife Stacey, words cannot express how grateful I am for your love and support. None of this would matter without you and our children in my life.

CHAPTER 1. INTRODUCTION

It is widely acknowledged that in order to mitigate and reverse the trend of the global climate change, steps must be taken to reduce carbon emissions. In this regard, the built environment is estimated to be responsible for approximately 39% of the energy-related global total, 11% of which resulted from manufacturing building materials and products such as steel and cement.[1] These emissions are known as embodied carbon (EC).

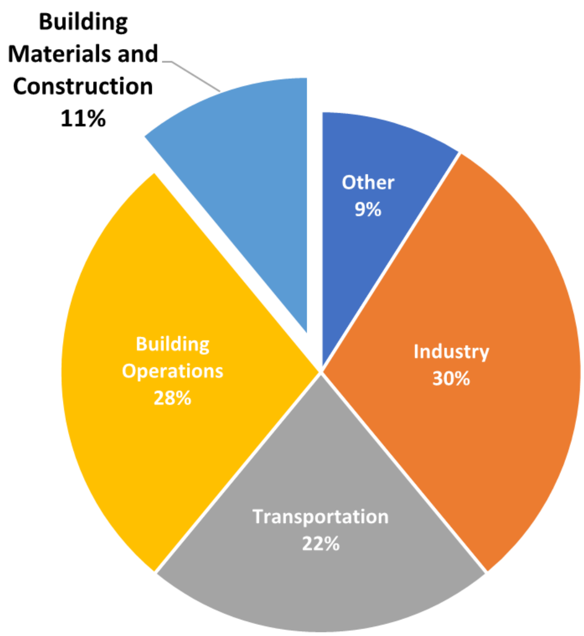


Figure 1 Global Co2 Emissions by Sector [31]

Given the magnitude, previous studies indicated that utilizing a mass timber system with cross laminated timber (CLT) panels can contribute to reducing EC from buildings, when compared to other structural systems.[2, 3, 4, 5] However, several barriers exist that prevent CLT from being selected for use in building projects. Efforts to overcome some barriers, such as code issues and limited supply, have been successful as the technology becomes more common place. [6] However, a critical barrier that still exists is its higher cost than other conventional materials.

In recent years, cost studies have been done on multiple public-works projects in the Pacific Northwest. The studies have shown that CLT mass timber structural systems are more expensive than traditional structural systems such structural steel framing. Both systems have long lifespans and perform well under seismic stress.[7,8] This leads to a difficult decision for project stakeholders. Is the reduction in EC worth the increase in costs over a more economical system with similar structural performance and life expectancy?

For environmental conscious project stakeholders the answer is yes, however there is often a large burden to justify the value of such expenditures. This applies especially to public building projects for entities such as municipalities, school districts and universities. Stakeholders for those types of projects have the duty to prioritize the economic impact of their decisions because funding comes from the public. It is expected that each design decision is weighed against the cost it takes to accomplish. To do this, many utilize the methodology of value management to define, maximize, and achieve the most ‘value-for-money’ on a project.[13]

For this reason, the value of CLT mass timber’s EC benefits must be properly demonstrated. The question becomes: How much EC is being saved and what is the cost impact? To answer this, a series of suitable structural system alternatives need to be compared. Unfortunately, a literature review performed at the onset of this study could not locate a framework for efficiently providing comparative EC and cost data. The use of current practices is time consuming and expensive which project stakeholders often cannot commit to. This reduces access to value comparison data which causes CLT mass timber structural systems to be dismissed due to its high-costs barrier, without proper consideration of the EC reduction benefits.

In response to the identified knowledge gap, the objective of this study is to create a conceptual model that automatically quantifies and visualizes the comparison data needed to justify the expense needed to reduce EC through selection of a structural system from a group of alternatives. It is hypothesized that this new model, titled the construction carbon reduction value model (CCRVM) will help promote CLT mass timber structural systems. The CCRVM aims to accomplish this by increasing the access that project stakeholders have to EC and construction cost comparison data by doing the following:

1. Reduce the overall time commitment required
2. Eliminate the need for specialized software
3. Simplify the ability to understand and share results.

To test the validity and usability of the CCRVM, a case study was performed using a new four-story classroom building that will be built at a major university in the Pacific Northwest region of the United States. Four alternative structural systems were inputted into the model to demonstrate how they compare on a cost and EC basis. These alternatives include:

1. **CLT with Steel Brace Frames -** CLT panels are supported by glued laminated timber (glulam) beams and columns with some miscellaneous hollow square section (HSS) steel framing. 3" concrete topping cover all floor panels. Steel wide flange brace frames act as the shear elements
2. **Steel Framed -** Conventional structural steel columns and beams support reinforced concrete slab on metal deck. Steel wide flange brace frames act as the shear elements.

3. **Post Tensioned Concrete -** Post tensioned concrete decks with integral concrete beams supported by concrete columns and concrete shear walls.
4. **CLT with CLT Shear Walls** – CLT panels supported by glulam beams and columns and some misc. HSS steel framing. 3" concrete topping cover all floor panels. CLT panels will also be used as shear walls.

The results of the case study concur with the findings of previous studies. That is, mass timber CLT structural systems result in lower EC when compared to steel and concrete systems. The two alternatives that utilized CLT mass timber (sourced from the Pacific Northwest region of North America) resulted in an approximate 42% to 52% reduction in embodied carbon when compared to the North American industry average Steel Framed alternative. When compared to the North American industry average Post Tensioned Concrete alternative they showed an approximate 63% to 69% reduction in EC. In both cases the CLT with CLT Shear Walls alternative showed the larger reduction.

Additionally, the case study also supported the notion that CLT mass timber does carry a cost premium. However, the estimated cost premiums were substantially lower than the percentages of embodied carbon reductions. The Steel Framed alternative resulted in the lowest estimated cost but was only a 13% reduction when compared to the CLT with Steel Braced Frames option and a 16% reduction from the CLT with CLT Shear Walls Option.

The use of the CCRVM streamlines the process of providing the value-based data that is described above. However, it contributes more than just comparing structural systems. The results of this study provide a framework for assessing how EC values relate to construction costs in general. Practitioners can utilize this framework in the future for the analysis of not just building structural systems, but any construction material.

CHAPTER 2. LITERATURE REVIEW

Structural System Selection

Many factors are affected by the structural system of a building, including the cost, duration, performance, safety, and aesthetics.[9] The selection of a structural system is also a challenging decision-making process due to recent advancements of various new technologies.[10] Due to this complexity, the decision is usually made through a collaborative effort of the owner, architect, and structural engineer with common criteria such as performance and costs. However, what is much less commonly considered is embodied carbon from a structural system.[11] In this regard, a complete understand of EC is required.

Lowering Embodied Carbon with CLT Mass Timber

Carbon emissions can be classified into two primary components: operational and embodied.[17] Operational emissions come from the energy consumed during building use such as HVAC, lighting, and plug loads. This accounts for the majority of carbon emissions and a large amount of attention has been placed on improving the energy efficiency of buildings. However, as mentioned earlier, studies show that embodied carbon (EC), or the energy used for manufacturing materials and the construction process of buildings, plays a large part as well.[18] Much of these emissions come from a building's structural system.[19] As a way to mitigate the impact, studies have shown that utilizing a mass timber structural system with engineered wood products such as glulam beams and CLT panels can lower emissions than traditional structural materials such as steel and concrete.[2, 3, 4, 5] These findings show the importance of demonstrating the value of a mass timber structural system from an environmental standpoint. However, doing so requires defining what "value" means as it relates the construction industry.

Value Management

A review of the body of knowledge on value revealed several different definitions for the term.

"Value relates to the assessment of the benefits brought by something in relation to the resources needed to achieve it. In the context of construction projects it is normally expressed as a ratio between a function and the whole life cost for that function...
Value = What You Get (or want) / What You Pay" (Chartered Institute of Building)

"Value is a relationship between function, time, cost and quality" (Value Management of Construction Projects).

"Value is an expression of the relationship between function and resources…
Value = Function / Resources" (Lawrence D. Miles Value Foundation).

"The concept of Value is based on the relationship between satisfying needs and objective and the resources required to achieve them." (Institute of Value Management)

The findings indicate that value in construction is generally accepted to be related to such indicators as function, cost, and quality but there is no universal definition of the term.[12] Part of the reason for this is that value is subjective.[13, 14] One group of stakeholders will have different objectives and goals than others. For example, one building owner may determine they can get the most value from a large, short-term facility whereas another owner believes they will get more value out of a more compact, long-term facility. To help determine the correct assessment of value for a project, many owners use the philosophy and management style called value management.[13]

Value management started over 70 years ago in the United States manufacturing industry. It was created to enhance the efficiency of producing existing products without compromising quality.[13] Over time it evolved into what is called value engineering which is a study with the aim of improving products that are still being designed, instead of products already in production.[13] It has gained popularity in the construction industry and is credited with improved performance and better delivery of construction projects.[14]

There are many excellent sources that describe the full process of value management also known as value methodology[15] but that is beyond the scope of this study. Most importantly, the cost needed to achieve what stakeholders want must be quantified and understood to perform value management. With this in mind, I have chosen to use the idea of value as an equation sourced from the Chartered Institute of Building[33] as shown in Eq. (1).

$$\text{Value} = \text{What You Get (or want)} / \text{What you Pay} \tag{1}$$

To use this in context, an owner may want to implement a superior exterior envelope and HVAC systems to reduce energy bills. The value equation becomes Eq. (2).

$$\text{Value} = \text{Reduction in Energy Use} / \text{What you Pay} \tag{2}$$

Structural systems do not typically have operational costs because they normally last the life of the building. Thus, one form of value comes from the performance capabilities of the system, which is a broad term used to encompass things like seismic resistance, durability, longevity, height, and span restrictions.[9] The value equation for structural performance looks like Eq. (3)

$$\text{Value} = \text{Increased Structural Performance} / \text{What you Pay} \tag{3}$$

To address the question, what happens when there are two structural systems that have comparable performance? The value of reducing EC should be considered as shown in Eq. (4).

$$\text{Value} = \text{Reduction of Embodied Carbon} / \text{What you Pay} \tag{4}$$

Equation (4) requires a construction cost estimate to budget "what you pay" which is the difference in costs between the alterative systems that are being compared. Then an assessment of environmental impacts called a Life Cycle Assessment is needed to determine what the reduction of embodied carbon is.

Life Cycle Assessment

The methodology commonly used for assessing embodied carbon impacts is known as a life cycle assessment (LCA). Impacts from activities such as raw material extraction, manufacturing, use, and end-of-life disposal are accounted for in order to provide an overall evaluation.[20] In the 1990s the International Organization for Standardization (ISO) developed a standard methodology for LCA that has four stages (Figure 2) Goal and scope definition; inventory analysis; life-cycle impact assessment; and interpretation.[20]

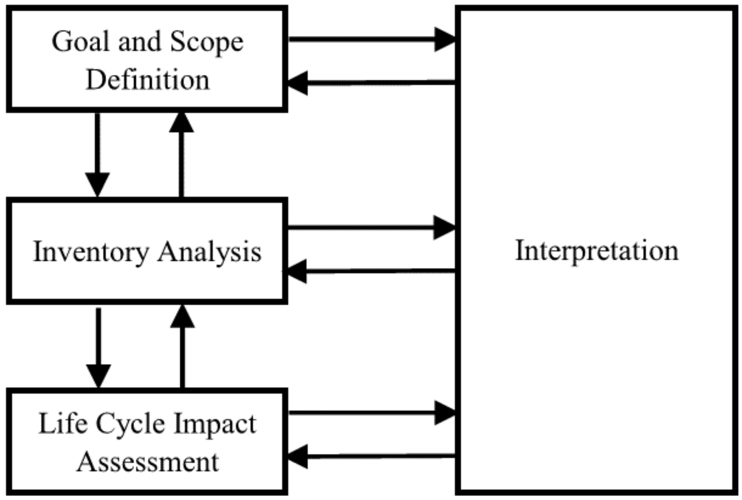


Figure 2 LCA framework [34]

Using the standardized calculation methods of ISO 14040 the embodied EC impact results are categorized by life-cycle stages.[18] The terms and definitions of these stages (also known as modules) vary between different sectors and regions. However, for this study I will refence them as defined in the European standard EN 15978 as shown in Figure 3.

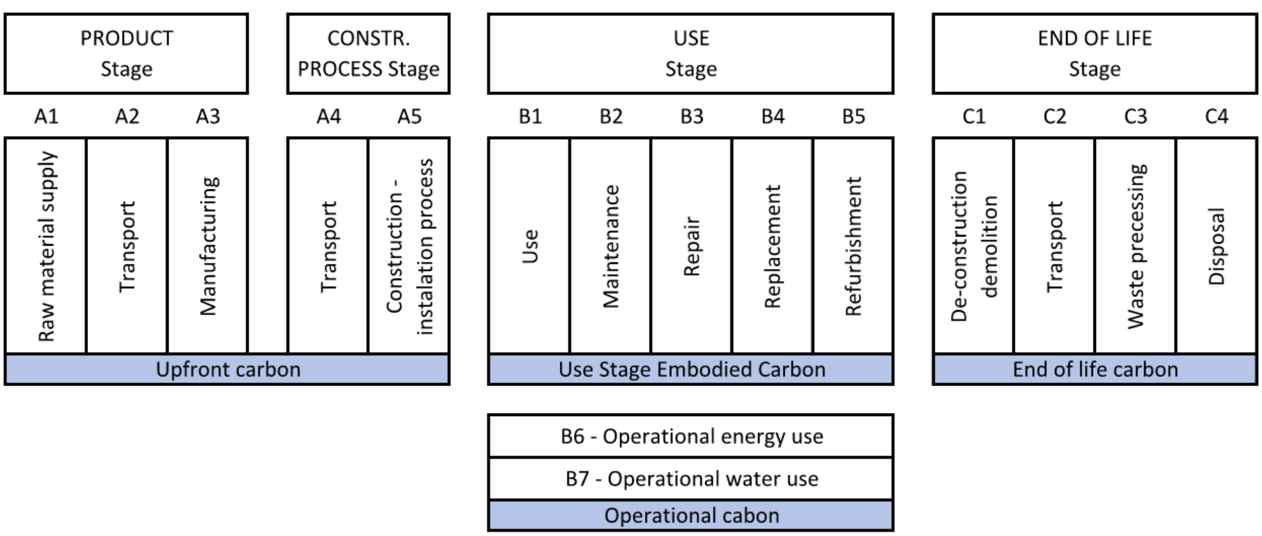


Figure 3 Lifecyle Stages Defined in EN 15978 [22]

Embodied carbon is considered to generally represent the carbon emissions from stages A1 – A5, B1 – B5 and C1 – C4. The term 'Upfront carbon' refers to the emissions from stages A1 – A5.[18] These are the emissions that occur before the building is occupied and are cited as compromising the majority of a material's embodied carbon impact.[18] They are deemed very important because of the urgency to reduce carbon emissions as soon as possible.[18] Upfront carbon was also observed to be the most common emissions to be reported in the form of an environmental product declaration (EPD).

EPDs are a document that consolidates the results of an LCA and are defined by (ISO) 14025 as a Type III declaration that "quantifies environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function".[21] EPDs are gaining much popularity as a source of information in the construction products market and are increasingly being used for product comparison for procurement decisions.[18] However, barriers do exist that prevent EPDs from being ideally suited for comparing the emissions of different products. The primary reason cited is that EPD data quality and specificity can vary widely.[18] Based on the data-quality factors presented in the EPD, a range of variability of the data quality should be identified.[18]

Gaps in Literature

There is a wide body of knowledge on the subjects of embodied carbon, LCA, and how CLT mass timber structural systems compare to other more traditional structural systems. However, there is a dearth studies specially aimed at investigating how construction costs relate to each of these subjects. More specifically, no studies were found with an objective of examining how the costs of construction projects are affected by design selections that aim to reduce embodied carbon. These identified gaps in the literature provided a point of departure for this study.

CHAPTER 3. RESEARCH METHODOLOGY

This study utilized the quantitative research methods of construction cost estimating and LCA by EPD. The results of these methods provided the means to program the CCRVM which aims to automatically model EC and cost data simultaneously from one set of inputs. A case study was then used to test the validity and usability of the CCRVM. Figure 4 outlines the research methods of this study.

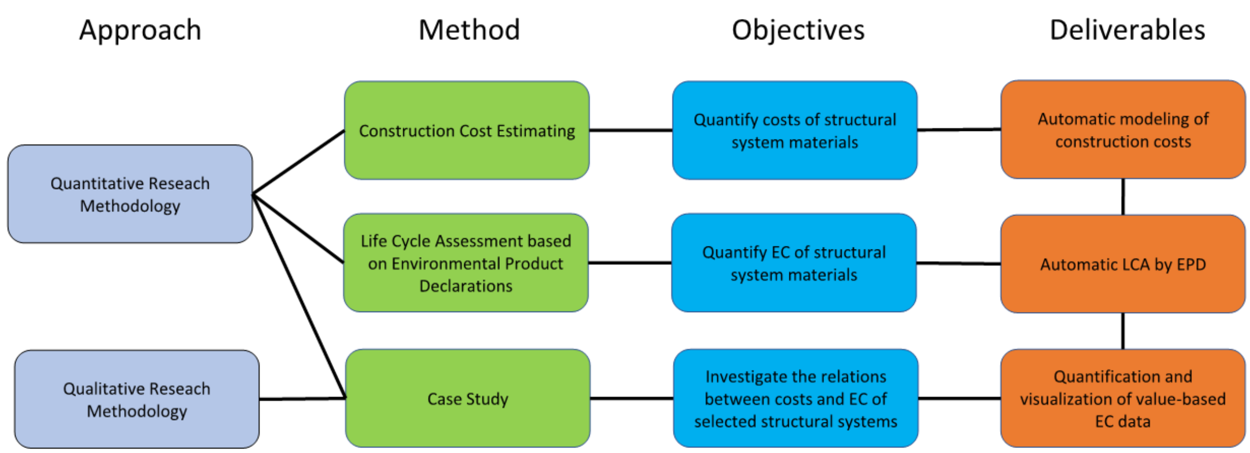


Figure 4 Research Methodology Outline

Quantifying Costs of Structural System Materials

To apply construction costs to inputted material quantities, the CCRVM uses the unit price estimating approach. The first step is to do a quantity take off of an item using a particular unit of measure (such as cubic yards of concrete). A unit price is then applied to the quantity that is inclusive of materials, equipment, labor, and the overhead & profit of the installing contractor.[24]

There are several sources for unit prices, such as published estimating guides, historical databases, and budgets directly from potential installing contractors.[24] The CCRVM does not use figures from a published estimating guide because they are typically representative of national average costs. To provide a more accurate cost estimate for the case study project, unit prices from a private construction cost consulting firm's historical database were used. These prices apply specifically to construction projects that are built in the same region as the case study. They are maintained through market research such as analysis of recent project bid results and contractor input.

Once a unit price is applied to a quantity, a single cost value will be calculated. However, it must be understood that this is a single value that falls within a range of potential costs.[23] This range of accuracy is traditionally represented as a +/- percentage range. The range applied should be increased or decreased based factors such as the completeness of the design documents and the quality of cost estimating data.[23] Example ranges by estimate type are provided by professional associates such as the Project Management Institute and the Association for the Advancement of Cost Engineering.

The ranges used for the CCRVM are based on design document milestones and are sourced from the same private consulting firm that provided the unit prices (see Table 1). These were developed by using industry accepted sources, such as the ones mentioned above, but with modifications based on the results of estimating construction costs over a 30-year firm history.

Table 1 CCRVM Estimate Ranges of Accuracy

Estimate Level	Range of Accuracy
Conceptual / Predesign	-10% to +20%
Schematic Design	-7.5% to +15%
Design Documents	-5% to +10%
Construction Documents	-2.5% to +5%

Quantifying EC of Structural System Materials

A primary function of the CCRVM is to provide comparative EC values for each structural alternative that is modeled. In order to do so a quantity of carbon dioxide equivalent (CO2e) must be applied to each material inputted. These CO2e quantities are acquired from EPDs which have been programed into the CCRVM. The benefit of using EPDs is they are easily acquired, third-party verified sources of environmental information.[27] Their use allows the CCRVM to be quickly updated for different regions and products. However, an issue with EPDs is the data quality can vary widely.[18, 27] Therefore the data from the EPDs is presented as a range of values in the CCRVM.

To apply the range of values to each EPD the framework from Waldman, B., et al.[18] was used. This framework uses the root mean square method to combine a series of data quality factors to produce an overall +/- percentage of uncertainty for the EPD. The default data quality factors from the study have been used and are shown in Table 2. The more specific an EPD, the tighter the data quality will be. An industry average EPD that does not apply to a single manufacturer and/or facility will have a much higher data quality range than one that does. Specifics on the EPDs used in the CCRVM will be discussed later on.

Additionally, a fifth factor called Supply Chain Specific is also described.[18] However, this relies on data that is not available in many cases. For this reason it was decided to not be included in the data quality calculations. This is the same approach as other tools that quantify GWP using EPDs, such as the EC3 tool from the Carbon Leadership Forum.[28]

Table 2 EPD data quality factors [18]

Factor	Option	Conditions	+ / - %
Manufacturer Specific	TRUE	Products in the EPD are declared by only ONE organization AND That organization owns the facility at which the relevant product is made	2%
	FALSE	FALSE for all other condition other than the TRUE condition described above. This includes EPDs that are described as representing a 'sector' or an industry	20%
Facility Specific	TRUE	*Manufacturer specific = True* AND Only One manufacturing facility used the EPD or data point to declare products	2%
	FALSE	FALSE for all other conditions other than the TRUE condition described above	20%
Product Specific	TRUE	*Manufacturer specific = True* AND No other product used the same EPD or data point	2%
	FALSE	FALSE for all other conditions other than the TRUE condition described	20%
Time Specific	TRUE	*Product specific = True* AND The declaration describes a single run of manufacturing that is no more than 90 calendar days long, AND no other batch or product used the	2%
	FALSE	FALSE for all other conditions other than the TRUE condition described	20%

Case Study

A crucial part of this study is to demonstrate the validity and usability of the CCRVM. To do this the case study methodology was used which is an effective way of answering questions that start with how, who and why.[25] Only a single case study is presented in this study which is sometimes criticized. However, a single case study can be deemed useful when researchers have "unusual research access to explore a significant phenomenon."[26] This is an appropriate description of the case study used here.

CHAPTER 4: CONSTRUCTION CARBON REDUCTION VALUE MODEL (CCRVM)

Improvement Over Current Practices

The research objective of creating the CCRVM was conceived with an end goal in mind: To streamline the process of comparing EC and construction costs for different building structural systems. Compared to current practices the CCRVM can:

1. Reduce the overall time commitment required
2. Eliminate the need for specialized software
3. Simplify the ability to understand and share results.

First, to reduce the overall time commitment required, the CCRVM aims to increase the efficiency in which value data is quantified. Current practices require separate construction cost estimates and LCA studies be done for each alternative. Experience tells that these must be performed completely independently and require differing sets of inputs as shown in Figure 5a. Then the data must be manually consolidated and visualized by the user. In response, the CCRVM uses a single set of inputs to perform both construction cost estimation and EC quantification and data summarization simultaneously. This streamlined process can be seen below in Figure 5b.

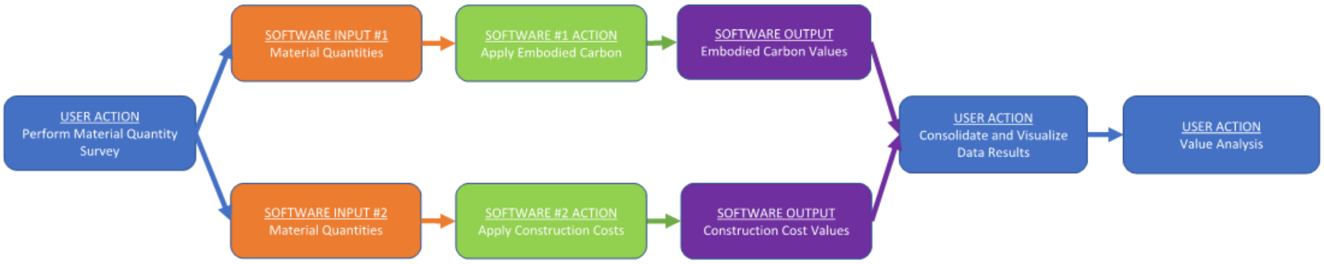


Figure 5a Existing Practices Process

Figure 5b CCRVM Process

Second, current practices frequently require the use specialized software which creates two potential barriers to project stakeholders. (1) It is common for cost estimating and LCA software to have licensing fees. (2) Training is needed to use specialized cost estimating and LCA software. In contrast the CCRVM is built in MS Excel. This saves project stakeholders time and money by removing the need for locating and hiring specialists in the use of proprietary tools.

Lastly, the CCRVM aims to support easy understanding and sharing of results. This is done through the use of data visualization, which aids in comprehension by reducing cognitive load and allowing for easier comparisons.[30] Print ready reporting is built in to facilitate the presentation of the data through graphs and tables. These allow even non-construction practitioners to effectively understand the results which is often required in publicly funded construction projects.

Structural System Alternatives

It is recommended that the selection of alternatives be a collaborative effort of the owner, architect, and structural engineer. For a proper comparison each alternative must meet the seismic performance and life expectancy requirements of the project. Inclusion of an underperforming system will result in disproportionate results. Once selected, a title and description of alternative is entered into the CCRVM as shown in Figure 6.

The other critical piece of input is the construction cost estimate level each alternative is priced at. A drop-down menu is used to select the documents level that material quantities are being surveyed from. This automatically adjusts the pricing accuracy range shown in the yellow cells. These ranges correspond with ranges presented in Table 1.

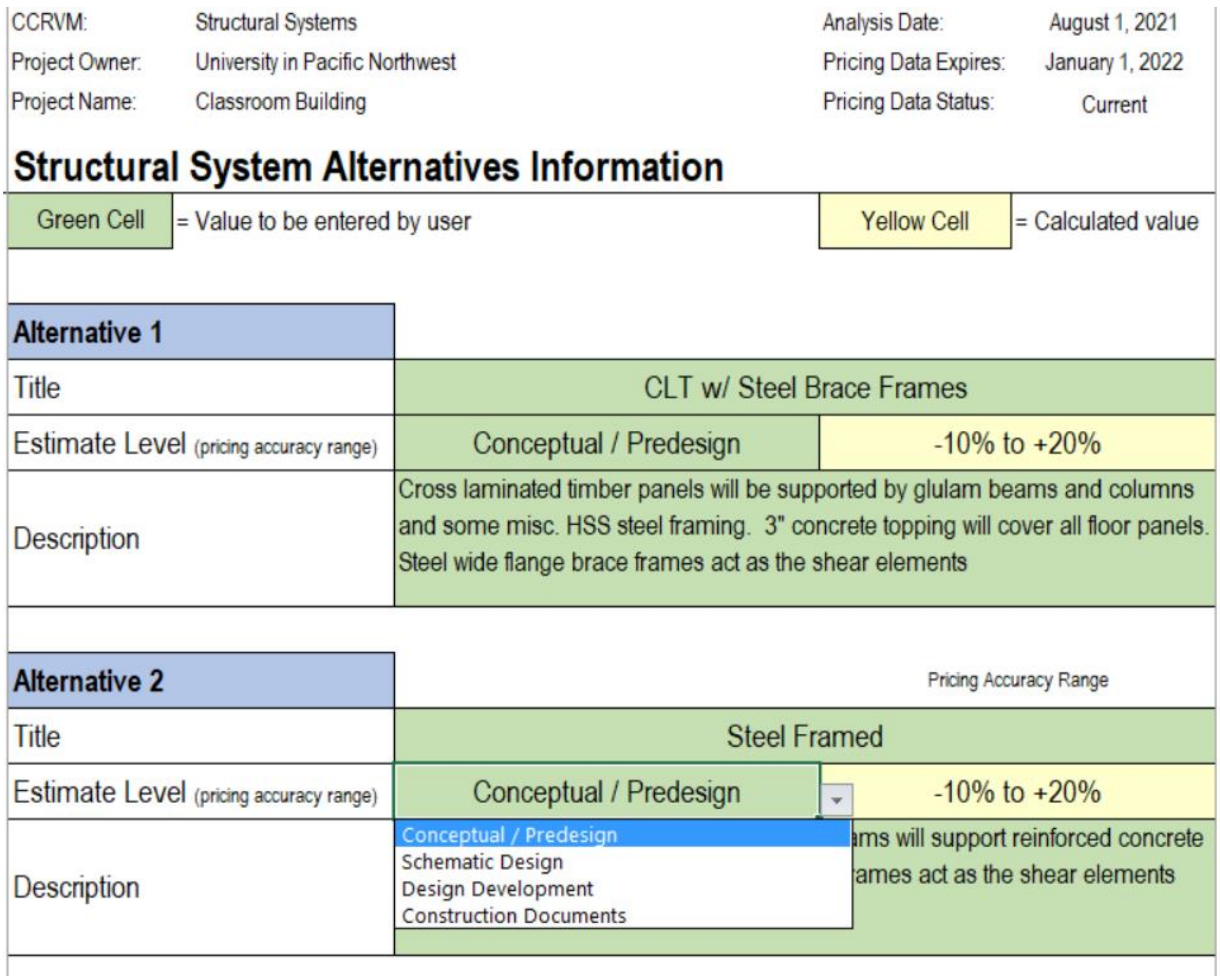


Figure 6 Structure System Alternatives Information

Material Quantity Inputs

After the alternatives selection, users then conduct a quantity survey of the materials that comprise each structural system. As seen in Figure 7 the user interface of the CCRVM is set up to be customized to receive these material inputs. Selecting Yes or No will expand or contract the data entry zones so that only the desired sections will be shown.

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Material Quantity Inputs

Alternative 1: CLT w/ Steel Brace Frames

Green Cell = Value to be entered by user | Yellow Cell = Calculated value

Cast in Place Concrete Inputs Required?		Structural Steel Inputs Required?	
Foundations	Yes	Pounds per SF Allowance	Yes
Walls	No	Wide Flange & HSS	No
Columns / Piers	Yes	Miscellaneous Metals	Yes
Slabs	Yes	Steel Deck	No
Elevated Decks	No		
Elevated Beams	No		
Mass Timber Inputs Required?		*Future Inputs*	
Board Feet per SF Allowance	Yes		
Glulam Columns & Beams	No		
Cross Laminted Timber Panels	Yes		

Figure 7 Required Inputs Selection

Figure 7 also shows built-in sections to receive material allowances per square foot. This is to accommodate structural information that is conceptual in the early design process. If more advanced information is received, the other entry zones are designed to receive detailed take offs.

Prompts are built in to ensure information is entered properly. For example Figure 8 shows when CIP Foundation Quantities are entered, the mix design, quantity, length, and width dimensions are required for each concrete foundation type. These inputs are required for cost estimation purposes.

CIP Foundation Quantities						
Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities			
			Quantity	Length - ft	Width - ft	Depth - ft
Spread Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	45.00	7.25	7.25	2.22
Continuous Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	1.00	376.00	3.00	1.50
Brace Frame Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	1.00	190.00	9.00	5.00

Figure 8 Example CIP Foundation Quantity Entries

This is the most technical part of using the CCRVM. Each piece of information must be quantified and entered properly to produce accurate construction costs and embodied carbon values. For this step, it is recommended to work with a team member with cost estimation experience.

Cost Estimation Details

The Cost Estimation Details section supports reviewing of all of the pricing calculations conducted by the CCRVM. No user inputs are required, values are automatically generated in the yellow cells as shown in Figure 9. However, the user should carefully review all generated figures, to make sure there were no errors in quantifying and or inputting material quantities. A pricing check figure is included in each section to assist with review. For example, Figure 10 shows Glulam Framing Pricing with a check figure of $20.90 per square foot of structure. A construction cost estimator with knowledge of glulam framed structures will know this figure falls within the expected range of cost per square foot pricing. A much lower or higher figure in the Check cell would indicate there is a problem with the material quantity that was inputted.

CCRVM:	Structural Systems
Project Owner:	University in Pacific Northwest
Project Name:	Classroom Building

Cost Estimation Details

Alternative 1: CLT w/ Steel Brace Frames

Green Cell	= Value to be entered by user	Yellow Cell	= Calculated value

Cast in Place Concrete Pricing (pricing per cubic yard automatically adjusts for mix design anc

Description	Concrete Pricing		Reinforcing Pricing		
	Quantity - cy	$ / CY	Quantity - lb	$ / lb	Q
Foundations	573.8	$234.00	73,214.8	$1.25	
Walls	0.0		0.0	$1.25	
Coumns / Piers	24.9	$228.00	11,571.2	$1.25	
Slabs (includes finishing)	378.8	$522.00	0.0	$1.25	
Elevated Decks (includes finishing)	0.0		0.0	$1.25	
Elevated Beams	0.0		0.0	$1.25	
Subtotal			**$105,982**		

Figure 9 Example Section of Cost Estimation Details

Glulam Framing Pricing

Description	Glulam Pricing		Extension	Check	
	Quantity - bf	$ / bf	Total $	$	Unit
Glulam Columns and Beams	123,240.2	$9.00	$1,109,161	$20.90	sf of structure
Subtotal			**$1,109,161**		

Figure 10 Example Section of Cost Estimation Details with Check figure

Life Cycle Analysis by EPD Details

This portion of the model displays the EC values that have been calculated for each material. Similar to the Cost Estimation Details all information shown in Figure 11 is automatically calculated.

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Life Cycle Analysis by EPD Details
Alternative 1: CLT w/ Steel Brace Frames

Green Cell	= Value to be entered by user	Yellow Cell	= Calculated value

Ready Mixed Concrete Embodied Carbon (kg CO2 automatically adjusts for different combination of mix designs)					
Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - cy	Qty Conversion- m3	kg CO2 / m3	kg CO2 Total	Range of Values
Concrete Structure	977.5	747.4	562.7	**420,530.5**	-40% to +40%

Fabricated Steel Reinforcement Embodied Carbon (P.T. cable quantity included at 2x)					
Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Total	Range of Values
Rebar and P.T. Cable Reinforcing	84,786.0	38.46	979.0	**37,650.6**	-40% to +40%

Figure 11 Example Section of Life Cycle Analysis by EPD Details

Figure 11 also shows how the material quantity figures are pulled from the inputs section and are then converted to the metric declared unit for each EPD. Conversion is required because the CCRVM is designed for use in the United States where it is standard to use imperial units for material quantity takeoffs. Each converted quantity then has the corresponding EC (kg of CO2e) applied per the EPDs listed in the Table 3.

Table 3 Environmental Product Declaration Information

Product	Owner	Number	Type	Scope	Data Quality Range
Ready Mixed Concrete	National Ready Mix Concrete Association	EPD10294	Industry Average	Product Stage	+ / - 40%
Facricated Steel Reinforcement	Concrete Reinforcing Steel Institute	070	Industry Average	Product Stage	+ / - 40%
Hot Rolled Structural Steel Sections	American Institute of Steel Construction	4789556099.102.1	Industry Average	Product Stage	+ / - 40%
Steel Roof and Floor Deck	Steel Deck Institute	4786052957.101.1	Industry Average	Product Stage	+ / - 40%
Glued Laminated Timber	American Wood Council	4788424634.104.1	Industry Average	Product Stage	+ / - 40%
Cross Laminated Timber (CLT); Brand name: Crosslam CLT by Structurlam	Structurlam Mass Timber Corporation	EPD124	Product Specific	Product Stage	+ / - 21%

The EPDs used in the model were selected to be as similar in nature as possible. All of them scope the Product Stage (as described in Chapter 2) and all except CLT is an industry average type. An industry average EPD for CLT could not be located, so the one listed was chosen for its close proximity to the case study project site. This product specific EPD results in a tighter data quality range (compared to industry average EPDs) according to the framework described in Table 2.

Summarization of Results

The CCRVM has two reports that summarizes the results produced from the previously described functions. The Embodied Carbon Reduction Value Analysis Summary and the Material Breakdown Summary. These reports are organized to efficiently communicate the quantification results needed to compare the value of each alternative. The lowest embodied carbon option and lowest cost option are automatically listed along with the embodied carbon and cost deltas of the two.

Each is accompanied by graphs to provide visual representation of the results. The scatter plot is effective at demonstrating that the total values shown in the summary reports are a single value that fall within a range of potential values. The ranges shown will expand and contract depending on selection of pricing accuracy range and material quantity inputs.

CHAPTER 5. CASE STUDY

Project Description

A future classroom building at a major university in Washington State was selected to demonstrate the functionality of the CCRVM as case study. The anticipated size is 53,400 gross building square feet over 4 floor levels. With permission from the architect of record, Figures 12 and 13 have been included for reference. This project was selected for the following reasons:

- Currently being designed which increases access to information from the architectural and structural design team.
- The massing of the project makes it suitable to utilize many different structural system configurations.
- Initial pricing studies had already been conducted which provided inspiration for this research project.

Figure 12 Case Study Project Level 2 Floor Plan, 13,990 SF (courtesy of Perkins+Will)

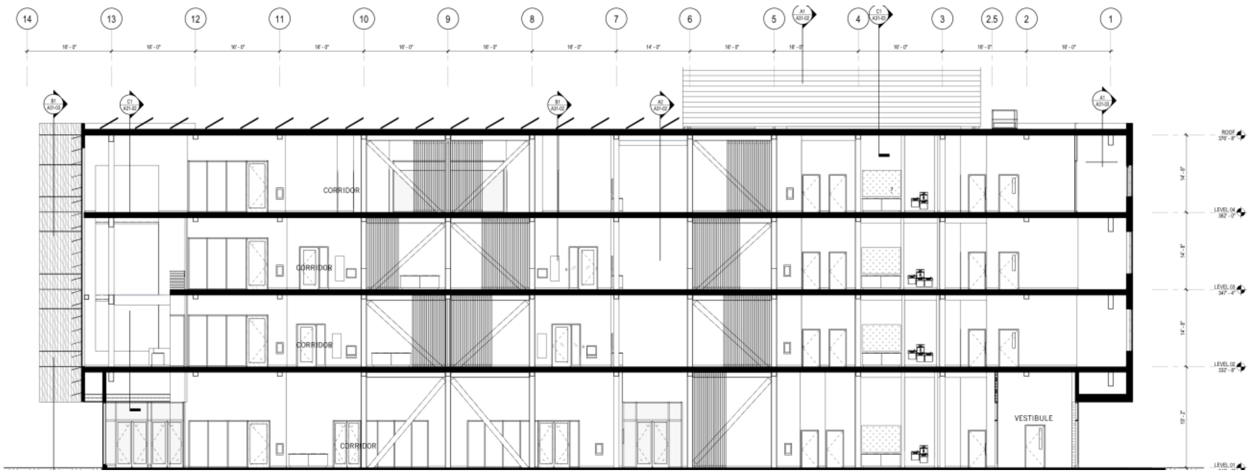


Figure 13 Case Study Project Section Cut (courtesy of Perkins+Will)

Structural System Alternatives

With the help of the structural engineering team, four conceptual alternative structural systems were generated. These alternatives are as follows:

1. **CLT with Steel Brace Frames** - CLT panels will be supported by glulam beams and columns and some misc. HSS steel framing. 3" concrete topping will cover all floor panels. Steel wide flange brace frames act as the shear elements

   Pros:
   - Reduced EC vs steel and concrete
   - Lightweight structure reduces foundations vs steel and concrete
   - Stakeholders like the aesthetic of exposing the structure

   Cons:
   - Increased cost (smaller labor pool and limited supply)
   - Less time tested than steel and concrete
   - Less weather resistive than steel and concrete

2. **Steel Framed** - Conventional structural steel columns and beams will support reinforced concrete slab on metal deck. Steel wide flange brace frames act as the shear elements.

   Pros:
   - Lowest cost
   - Readily available

   Cons:
   - Stakeholders do not like the aesthetic of exposing the structure, which requires it to be covered with architectural elements.

- Higher carbon emissions vs mass timber CLT

3. **Post Tensioned Concrete -** Post tensioned concrete decks with integral concrete beams will be supported by concrete columns and concrete shear walls.

   Pros:
   - Rigid structure with high vibration resistance
   - Readily available

   Cons:
   - Slowest installation time vs CLT mass timber and Steel
   - Largest foundation requirements
   - Highest carbon emissions vs steel and mass timber CLT

4. **CLT with CLT Shear Walls** – CLT panels will be supported by glulam beams and columns and some misc. HSS steel framing. 3" concrete topping will cover all floor panels. CLT panels will also be used as shear walls.

   Pros:
   - Reduced carbon emissions vs steel and concrete
   - Lightweight structure reduces foundations vs steel and concrete
   - Stakeholders like the aesthetic of exposing the structure

   Cons:
   - Increased cost (smaller labor pool and limited supply)
   - Lateral design is still experimental and would increase permitting efforts with building officials
   - Increased shear wall area reduces ability for transparency in design.

Out of the four alternatives listed, the project team decided to move forward with the CLT with Steel Brace Frames option. The pros of reducing carbon emissions and affinity for an exposed wood structure aesthetic outweighed the primary con of higher cost. The CLT with CLT Shear Walls alternative was also considered but was disregarded primarily due to the risks of going with a more experimental lateral design.

Case Study Results

The quantification results for each alternative are summarized in a series of automated reports. The Material Breakdown Summary contains two parts, the first part presents the EC totals for each material that makes up an alternative. The second presents the cost totals for each. The first

EC section can be seen in Figure 14 shows that Alt 3 - Post Tensioned Concrete would have the highest total embodied carbon emissions and Alt 4 - CLT with CLT Shear Walls would have the lowest. Another key observation is ready mixed concrete represents the largest source of embodied carbon in all alternatives, regardless of the type of structural system.

The second cost section shown in Figure 15 indicates that Alt 2 – Streel Framed is estimated to be the least expensive alternative and Alt 4 - CLT with CLT Shear Walls would be the most expensive. The accompanying graph visually shows that each alternative is relatively close in cost. Whereas the graph in Figure 14 shows disparity between the embodied carbon totals of each alternative.

CCRVM:	Structural Systems	Analysis Date:	August 1, 2021
Project Owner:	University in Pacific Northwest	Pricing Data Expires:	January 1, 2022
Project Name:	Classroom Building	Pricing Data Status:	Current

Material Breakdown Summary

Emobided Carbon Totals per Material				
Description	Alt 1 CLT w/ Steel Brace Frames	Alt 2 Steel Framed	Alt 3 Post Tensioned Concrete	Alt 4 CLT with CLT Shear Walls
Ready Mixed Concrete	420,530	637,855	1,712,337	340,525
Fabricated Steel Reinforcement	37,651	51,952	325,877	25,192
Structural Steel	168,114	476,661	30,458	84,240
Steel Decking	0	165,463	0	0
Glued Laminated Timber	39,896	0	0	39,896
Cross Laminated Timber Panels	101,425	0	0	155,648
Totals	**767,617**	**1,331,933**	**2,068,672**	**645,502**

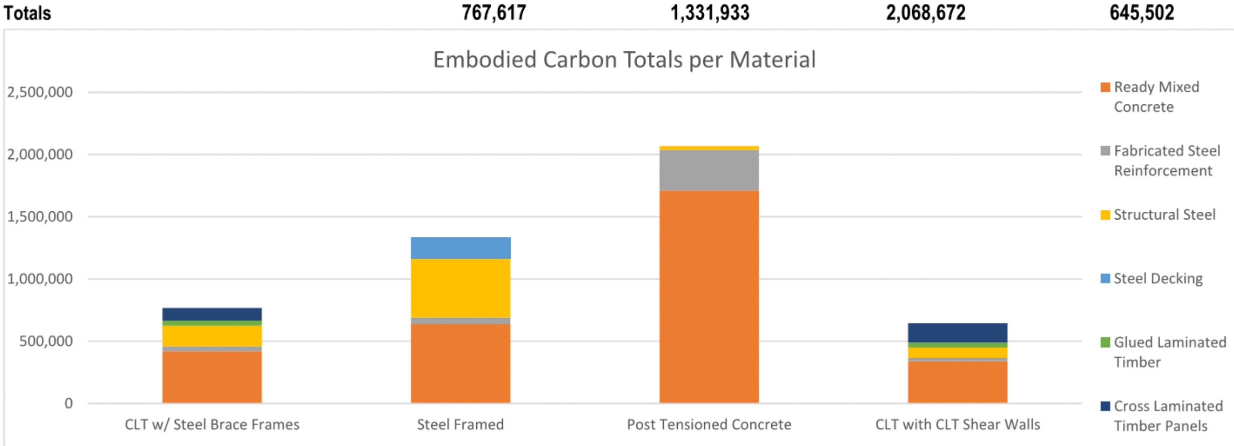


Figure 14 Case Study Embodied Carbon Totals per Material

CCRVM:	Structural Systems	Analysis Date:	August 1, 2021
Project Owner:	University in Pacific Northwest	Pricing Data Expires:	January 1, 2022
Project Name:	Classroom Building	Pricing Data Status:	Current

Material Breakdown Summary

Estimated Construction Cost Totals per Material				
Description	Alt 1 CLT w/ Steel Brace Frames	Alt 2 Steel Framed	Alt 3 Post Tensioned Concrete	Alt 4 CLT with CLT Shear Walls
Ready Mixed Concrete	$540,157	$765,212	$4,029,498	$443,727
Fabricated Steel Reinforcement	$105,982	$146,241	$651,934	$70,913
Structural Steel	$1,311,158	$3,118,260	$330,234	$780,681
Steel Decking	$0	$225,378	$0	$0
Glued Laminated Timber	$1,109,161	$0	$0	$985,921
Cross Laminated Timber Panels	$1,794,210	$0	$0	$2,681,250
Totals	**$4,860,669**	**$4,255,090**	**$5,011,666**	**$4,962,492**

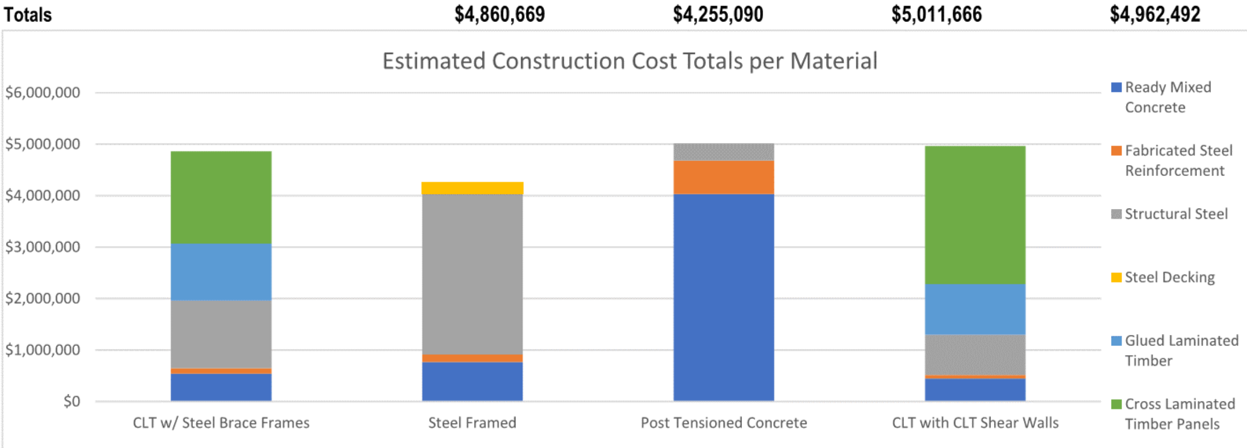


Figure 15 Case Study Estimated Construction Cost Totals per Material

The Embodied Carbon Reduction Value Analysis Summary is shown in Figure 16. The results of the case study show that Alt 4 - CLT with CLT Shear Walls provides a 52% reduction in EC when compared to the least expensive Alt 2 - Steel Framed. The cost premium for selecting the Alt 2 is estimated to be 16% over Alt 4. This data then culminates to answer the value equation which is for every dollar spent .88 kilograms of CO_2e emissions is reduced. The results are also shown graphically in Figure 17.

CCRVM:	Structural Systems	Analysis Date:	August 30, 2021
Project Owner:	University in Pacific Northwest	Pricing Data Expires:	January 1, 2022
Project Name:	Classroom Building	Pricing Data Status:	Current

Embodied Carbon Reduction Value Analysis Summary

Estimated Totals						
Description	Total Embodied Carbon (kg CO2e)			Total Construction Cost (US$)		
	Low Range	Estimated Value	High Range	Low Range	Estimated Value	High Range
Alt 1: CLT w/ Steel Brace Frames	559,673	767,617	1,055,392	4,418,790	$4,860,669	5,832,802
Alt 2: Steel Framed	951,380	1,331,933	1,864,706	3,868,264	$4,255,090	5,106,108
Alt 3: Post Tensioned Concrete	1,477,623	2,068,672	2,896,141	4,556,060	$5,011,666	6,013,999
Alt 4: CLT with CLT Shear Walls	478,531	645,502	874,130	4,511,356	$4,962,492	5,954,991

Lowest Embodied Carbon Option =	CLT with CLT Shear Walls
Lowest Construction Cost Option =	Steel Framed
Embodied Carbon Reduction of CLT with CLT Shear Walls vs. Steel Framed =	-686,430 kg CO2e
Percentage Delta	-52%
Construction Cost Delta of CLT with CLT Shear Walls vs. Steel Framed =	$707,402
Percentage Delta	14%
Embodied Carbon Reduction per Building GSF for CLT with CLT Shear Walls vs. Steel Framed =	-13 kg CO2e / GSF
For Every Dollar Spent, Embodied Carbon is Reduced By: Value Equation = kg CO2e Reduction / $ Premium	**-.97 kg CO2e**
The Estimated Price for Reducing a kg of Embodied Carbon:	**$1.03**

Figure 16 Case Study Embodied Carbon Reduction Value Analysis Summary

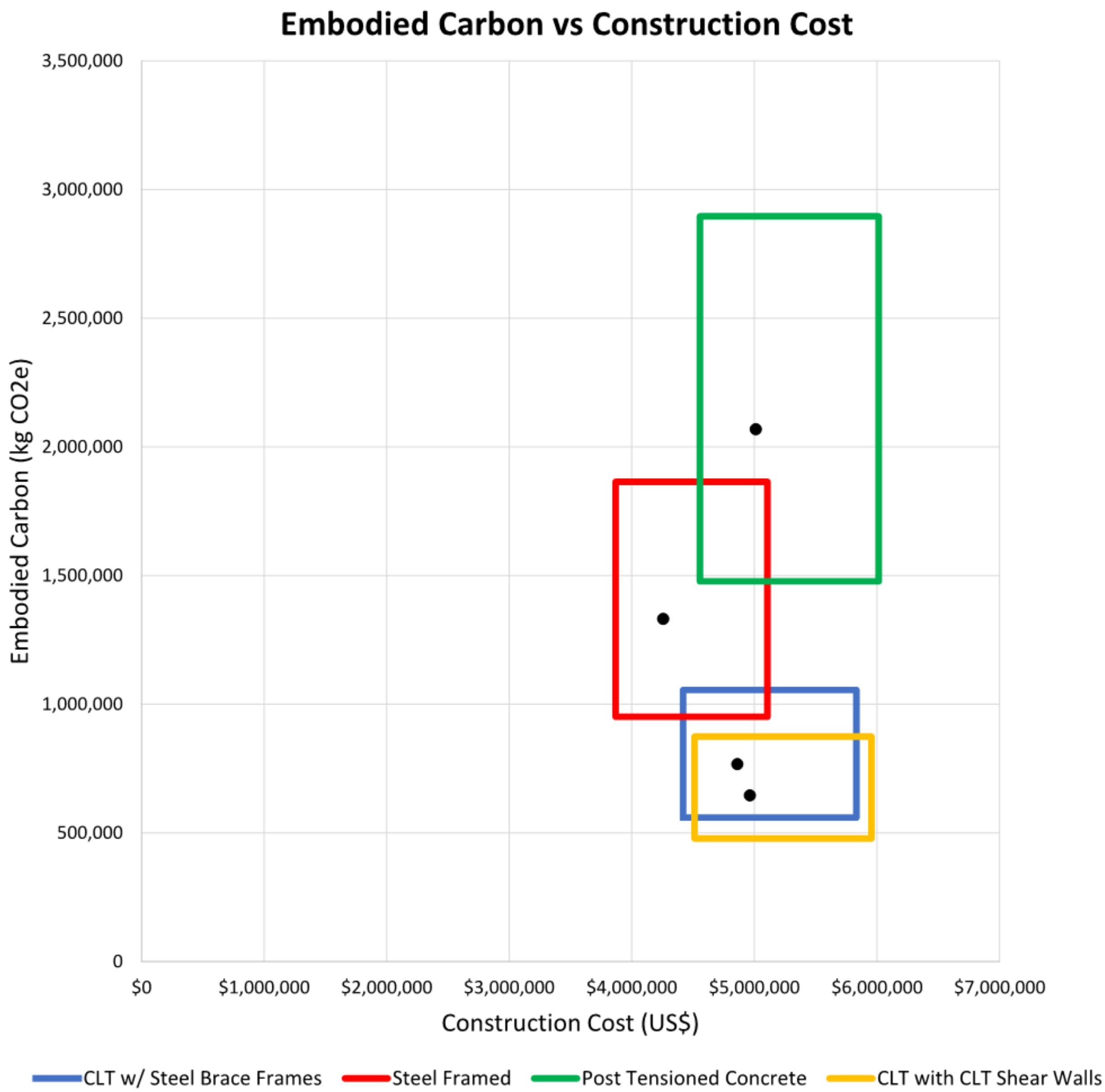


Figure 17 Case Study Embodied Carbon vs Construction Cost Scatter Plot

Several important observations can be made from Figure 17. First, the two alternatives that utilize CLT have a much tighter embodied carbon range than the steel and concrete alternatives. This represents the difference in results from using an industry average EPD versus a product specific EPD. Second, it can be observed that several of the ranges overlap. These overlaps demonstrate the range of values where multiple alternatives could have the same result. This is due to the conceptual nature of the information being utilized.

With this in mind, the large overlap of the two CLT options show that it cannot be confirmed with high certainty which alternative will have lower embodied carbon and which will be less expensive. On the other hand, the large distance between ranges shows high certainty that the CLT options will result in lower embodied carbon emissions that the Post Tensioned concrete alternative.

CHAPTER 6. CONCLUSION

To mitigate and reverse the trend of the global climate change, project stakeholders must consider selecting products that can reduce EC in the built environment. In this regard, replacing conventional materials (steel, concrete) in a structural system with mass timber CLT has shown to have a positive impact.[2, 3, 4, 5] However, selection of a mass timber CLT system from a group of conventional alternatives often faces a high-cost barrier. Project stakeholders can overcome the barrier by demonstrating the value a project gains from reducing EC.

To demonstrate this value, the EC and construction cost values for multiple alternatives must be quantified and compared. However, the current practices are not integrated and require a significant amount of time and resources. To solve this problem, this study was conducted with the goal of achieving the following three objectives. (1) Develop the CCRVM to streamline the process of comparing structural system alternatives. (2) Test the functionality of the CCRVM using the case study research method. (3) Quantify and present the value of reducing EC by selecting a mass timber CLT structural system.

First, to create the CCRVM, a review of the existing literature was conducted to examine how value is defined in the construction industry and what methods are used to quantify EC and construction costs. This led to the research methods of LCA by EPD and unit price estimating being combined into a single framework built in Excel. As a result, a conceptual model, titled CCRVM, was developed to automatically quantify, compare, and visualize construction cost and EC data from a single set of material inputs for each alternative.

Second, the CCRVM was tested using a case study project. It was shown to be a functional and efficient way of quantifying and comparing the construction costs and EC of building structural system alternatives, as follows: (1) It was confirmed that reducing user requirements through automation of multiple functions resulted in efficiencies over the current practices that largely lack integration; (2) utilizing a single framework equated to significant time savings when compared to using sperate tools and then consolidating the data manually.

Lastly, the case study was also used to accomplish the objective of quantifying and presenting the value of reducing EC by selecting a mass timber CLT structural system. A summary of the result is shown in Figure 18.

Embodied Carbon Reduction of CLT with CLT Shear Walls vs. Steel Framed =	-686,430 kg CO2e
Percentage Delta	-52%
Construction Cost Delta of CLT with CLT Shear Walls vs. Steel Framed =	$707,402
Percentage Delta	14%
Embodied Carbon Reduction per Building GSF for CLT with CLT Shear Walls vs. Steel Framed =	-13 kg CO2e / GSF

Figure 18 Excerpt of Case Study Embodied Carbon Reduction Value Analysis Summary

The case study results showed that selection of a CLT with CLT Shear Walls alternative over a Steel Framed alternative results in a 52% decrease in EC while only requiring a 14% increase in costs. Additionally, the other CLT alternative that uses steel brace frames in lieu of CLT shear walls provided a 42% decrease in EC with a 12% increase in costs. Project stakeholders could choose either alternative for a significant drop in EC. They also have the information to decide which CLT system suits the project best based on spending less money or reducing EC by the maximum amount. These results show the CCRVM can be an asset to project stakeholders that wish to reduce EC through selection of a mass timber CLT structural system.

In summary, the CCRVM shows promise to contribute several benefits to project stakeholders. It improves efficiency over current practices through a streamlined quantification, comparison, and visualization process. It supports “informed” decision making early in the design stages for value management. Finally, it provides a framework that can be utilized to examine how other construction materials behave on a cost and EC basis.

Limitations

While this study was successful in contributing a new framework for efficiently comparing costs and EC in structural systems, the following limitations are acknowledged.

- Construction costs and EC values can differ greatly based on the geographic area a project is located in. To use the CCRVM for other areas, regional specific cost and EC data should be added. The CCRVM is designed to program new units for each.
- The CCRVM is not for use to predict cost comparisons of future projects. The unit pricing used is only applicable to construction work that will occur within a 6 months’ time. The cost comparison results are in what is called “today’s dollars” which means any future pricing fluctuations are not accounted for. An expiration notification is programed in CCRVM to notify the users if pricing is valid.
- Only one case study was conducted to validate and test the CCRVM. While showing that the CCRVM is suitable for use on projects similar to the case study project, this may not be the case for other projects that greatly differ in type and scale.

- The CCRVM is designed to produce *comparative* EC and construction cost data not *total* EC and construction cost data. Inputs that are the exact same for each alternative may be excluded from an analysis because they do not influence comparison results.

Future Study

Future study is suggested on testing and validating the CCRVM with extended data sets. This can contribute to harnessing predictive analytics for improving the process of making structural design decisions. Predictive analytics refers to making predictions of future outcomes based on parameters such as historical data, machine learning and artificial intelligence.[32] Assessing structural alternatives for many different project types and sizes should be done. With enough use cases conducted, a future study could yield results that allow researchers to enhance the CCRVM to automatically present structural system options for reducing EC. This would theoretically eliminate the need for structural engineering assistance with generating the alternatives to be tested. The result would be an increase in the efficiency of selecting a structural system with the goal of reducing EC.

BIBLIOGRAPHY

1. Global Status Report for Buildings and Construction 2019. IEA. Accessed July 5th, 2021. https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019.

2. Pierobon, Francesca, Huang, Monica, Simonen, Kathrina, Ganguly, Indroneil. Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest. *Journal of Building Engineering*. 2019;26:100862. doi:10.1016/j.jobe.2019.100862

3. Crawford, Robert H, Cadorel, Xavier. A Framework for Assessing the Environmental Benefits of Mass Timber Construction. *Procedia engineering*. 2017;196:838-846. doi:10.1016/j.proeng.2017.08.015

4. Dodoo, Ambrose, Gustavsson, Leif, Sathre, Roger. Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems. *Energy and buildings*. 2014;82:194-210. doi:10.1016/j.enbuild.2014.06.034

5. Skullestad, Julie Lyslo, Bohne, Rolf André, Lohne, Jardar. High-rise Timber Buildings as a Climate Change Mitigation Measure – A Comparative LCA of Structural System Alternatives. Energy procedia. 2016;96:112-123. doi:10.1016/j.egypro.2016.09.112

6. Laguarda Mallo, Maria Fernanda. Critical Factors in the Willingness to Adopt Innovative Woodbased Building Materials in the Construction Industry: The Case of CLT. Published online 2017.

7. Izzi, Matteo, Casagrande, Daniele, Bezzi, Stefano, Pasca, Dag, Follesa, Maurizio, Tomasi, Roberto. Seismic behaviour of Cross-Laminated Timber structures: A state-of-the-art review. *Engineering structures*. 2018;170:42-52. doi:10.1016/j.engstruct.2018.05.060

8. Gioncu V, Mazzolani, Federico M. *Seismic Design of Steel Structures*. CRC Press/Taylor & Francis; 2014.

9. Chen W-F, Lui, E. M. *Principles of Structural Design*. CRC/Taylor & Francis; 2006.

10. Balali, Vahid, Zahraie, Banafsheh, Roozbahani, Abbas. Integration of ELECTRE III and PROMETHEE II Decision-Making Methods with an Interval Approach: Application in Selection of Appropriate Structural Systems. *Journal of computing in civil engineering*. 2014;28(2):297-314. doi:10.1061/(ASCE)CP.1943-5487.0000254

11. Polat, Gul, Turkoglu, Harun, Damci, Atilla. Structural System Selection Using the Integration of Multi-Attribute-Decision-Making (MADM) Methods. *Periodica polytechnica Architecture*. 2018;49(1):38-46. doi:10.3311/PPar.12670

12. Salvatierra-Garrido, Jose, Pasquire, Christine. Value theory in lean construction. *Journal of financial management of property and construction*. 2011;16(1):8-18. doi:10.1108/13664381111116043

13. Kelly J, Male, Steven, Graham, Drummond. *Value Management of Construction Projects*. Second edition. Wiley Blackwell; 2015.

14. Oke, Ayodeji E, Aigbavboa, Clinton O. *Sustainable Value Management for Construction Projects*. Springer International Publishing AG; 2017. doi:10.1007/978-3-319-54151-8

15. About the Value Methodology. SAVE. https://www.value-eng.org/page/AboutVM Accessed July 5th 2021.

16. National Research Council . Committee on Ecological Impacts of Climate Change. *Ecological Impacts of Climate Change*. National Academies Press; 2008.

17. Ibn-Mohammed, T, Greenough, R, Taylor, S, Ozawa-Meida, L, Acquaye, A. Operational vs. embodied emissions in buildings—A review of current trends. *Energy and buildings*. 2013;66:232-245. doi:10.1016/j.enbuild.2013.07.026

18. Brook Waldman, Monica Huang, Kathrina Simonen. Embodied carbon in construction materials: a framework for quantifying data quality in EPDs. *Buildings & Cities*. 2020;1(1). doi:10.5334/bc.31

19. Skullestad, Julie Lyslo, Bohne, Rolf André, Lohne, Jardar. High-rise Timber Buildings as a Climate Change Mitigation Measure – A Comparative LCA of Structural System Alternatives. *Energy procedia*. 2016;96:112-123. doi:10.1016/j.egypro.2016.09.112

20. Cabeza, Luisa F, Rincón, Lídia, Vilariño, Virginia, Pérez, Gabriel, Castell, Albert. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable & sustainable energy reviews*. 2014;29:394-416. doi:10.1016/j.rser.2013.08.037

21. Environmental labels and declarations - Type III environmental declarations - Principles and procedures. ISO. Accessed July 5th 2021. https://www.iso.org/obp/ui#iso:std:iso:14025:ed-1:v1:en

22. Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon. WorldGBC. Accessed July 25th 2021. https://www.worldgbc.org/embodied-carbon

23. Larry Dysert. Is Estimate Accuracy an Oxymoron? *Cost engineering (Morgantown, W Va)*. 2007;49(1):32.

24. Holm L, Schaufelberger, John. *Construction Cost Estimating*. First edition. Routledge/Taylor & Francis Group; 2021.

25. Yin, Robert K. *Case Study Research: Design and Methods*. Sage Publications; 2013.

26. Davies, Andrew, Gann, David, Douglas, Tony. Innovation in Megaprojects: Systems Integration at London Heathrow Terminal 5. *California management review*. 2009;51(2):101-125. doi:10.2307/41166482

27. Gelowitz, M.D.C, McArthur, J.J. Insights on environmental product declaration use from Canada's first LEED® v4 platinum commercial project. *Resources, conservation and recycling*. 2018;136:436-444. doi:10.1016/j.resconrec.2018.05.008

28. EC3. Carbon Leadership Forum. Accessed Augst 7th, 2021. https://carbonleadershipforum.org/what-we-do/initiatives/ec3/

29. Ira Iosebashvili. The First Rule of Microsoft Excel -- Don't Let On You're Good at It --- Spreadsheet experts face barrage of help requests in office; 'run the other way' *The Wall Street journal. Eastern edition*. 2018.

30. Bresciani, S, Eppler, M.J. The Benefits of Synchronous Collaborative Information Visualization: Evidence from an Experimental Evaluation. *IEEE transactions on visualization and computer graphics*. 2009;15(6):1073-1080. doi:10.1109/TVCG.2009.188

31. New Buildings: Embodied Carbon. Architecture 2030. Accessed Augst 13th, 2021. https://architecture2030.org/new-buildings-embodied/

32. Kumar V, Ram, Mangey. *Predictive Analytics : Modeling and Optimization*. First edition. CRC Press; 2021.

33. Chartered Institute of Building. Value in building design and construction. Designing Buildings Wiki. Updated April 27, 2021. Accessed August 19th, 2021. https://www.designingbuildings.co.uk/wiki/Value_in_building_design_and_construction.

34. Muralikrishna IV, Manickam, Valli. Environmental Management : Science and Engineering for Industry. Butterworth-Heinemann, an imprint of Elsevier; 2017.

CONSTRUCTION CARBON REDUCTION VALUE MODEL (CCRVM)
EXECUTIVE SUMMARY

MODEL INFORMATION

CCRVM Type:	Building Structural Systems
Last Updated:	July, 2021
Pricing Market Area:	Western Washington State
Pricing Data Expires:	January 1, 2022

CONTACT INFORMATION

Organization:	University of Washington
Contact Name:	Matt Wiggins
E-mail:	mwiggity@uw.edu

PROJECT INFORMATION

Owner:	University in Pacific Northwest	Analysis Date:	August 30, 2021
Name:	Classroom Building	Building Area:	53,400 GSF
Location:	Western, WA	Floor Structure Area (SoG not included):	39,615 SF
		Roof Structure Area:	13,460 SF

Project Description:	New 4 story university classroom building

CCRVM:	Structural Systems		Analysis Date:	August 30, 2021
Project Owner:	University in Pacific Northwest		Pricing Data Expires:	January 1, 2022
Project Name:	Classroom Building		Pricing Data Status:	Current

Structural System Alternatives Information

Green Cell	= Value to be entered by user	Yellow Cell	= Calculated value

Alternative 1		
Title	CLT w/ Steel Brace Frames	
Estimate Level (pricing accuracy range)	Conceptual / Predesign	-10% to +20%
Description	Cross laminated timber panels will be supported by glulam beams and columns and some misc. HSS steel framing. 3" concrete topping will cover all floor panels. Steel wide flange brace frames act as the shear elements	

Alternative 2		Pricing Accuracy Range
Title	Steel Framed	
Estimate Level (pricing accuracy range)	Conceptual / Predesign	-10% to +20%
Description	Conventional structural steel columns and beams will support reinforced concrete slab on metal deck. Steel wide flange brace frames act as the shear elements	

Alternative 3		Pricing Accuracy Range
Title	Post Tensioned Concrete	
Estimate Level (pricing accuracy range)	Conceptual / Predesign	-10% to +20%
Description	Post tensioned concrete decks will integral concrete beams will be supported by concrete columns and concrete shear walls	

Alternative 4		Pricing Accuracy Range
Title	CLT with CLT Shear Walls	
Estimate Level (pricing accuracy range)	Conceptual / Predesign	-10% to +20%
Description	Cross laminated timber panels will be supported by glulam beams and columns and some misc. HSS steel framing. 3" concrete topping will cover all floor panels. CLT panels will be used as shear walls	

CCRVM:	Structural Systems	Analysis Date:	August 30, 2021
Project Owner:	University in Pacific Northwest	Pricing Data Expires:	January 1, 2022
Project Name:	Classroom Building	Pricing Data Status:	Current

Embodied Carbon Reduction Value Analysis Summary

Estimated Totals

Description	Total Embodied Carbon (kg CO2e)			Total Construction Cost (US$)		
	Low Range	Estimated Value	High Range	Low Range	Estimated Value	High Range
Alt 1: CLT w/ Steel Brace Frames	559,673	767,617	1,055,392	4,418,790	$4,860,669	5,832,802
Alt 2: Steel Framed	951,380	1,331,933	1,864,706	3,868,264	$4,255,090	5,106,108
Alt 3: Post Tensioned Concrete	1,477,623	2,068,672	2,896,141	4,556,060	$5,011,666	6,013,999
Alt 4: CLT with CLT Shear Walls	478,531	645,502	874,130	4,511,356	$4,962,492	5,954,991

Lowest Embodied Carbon Option =	CLT with CLT Shear Walls

Lowest Construction Cost Option =	Steel Framed

Embodied Carbon Reduction of CLT with CLT Shear Walls vs. Steel Framed =	-686,430 kg CO2e
Percentage Delta	-52%

Construction Cost Delta of CLT with CLT Shear Walls vs. Steel Framed =	$707,402
Percentage Delta	14%

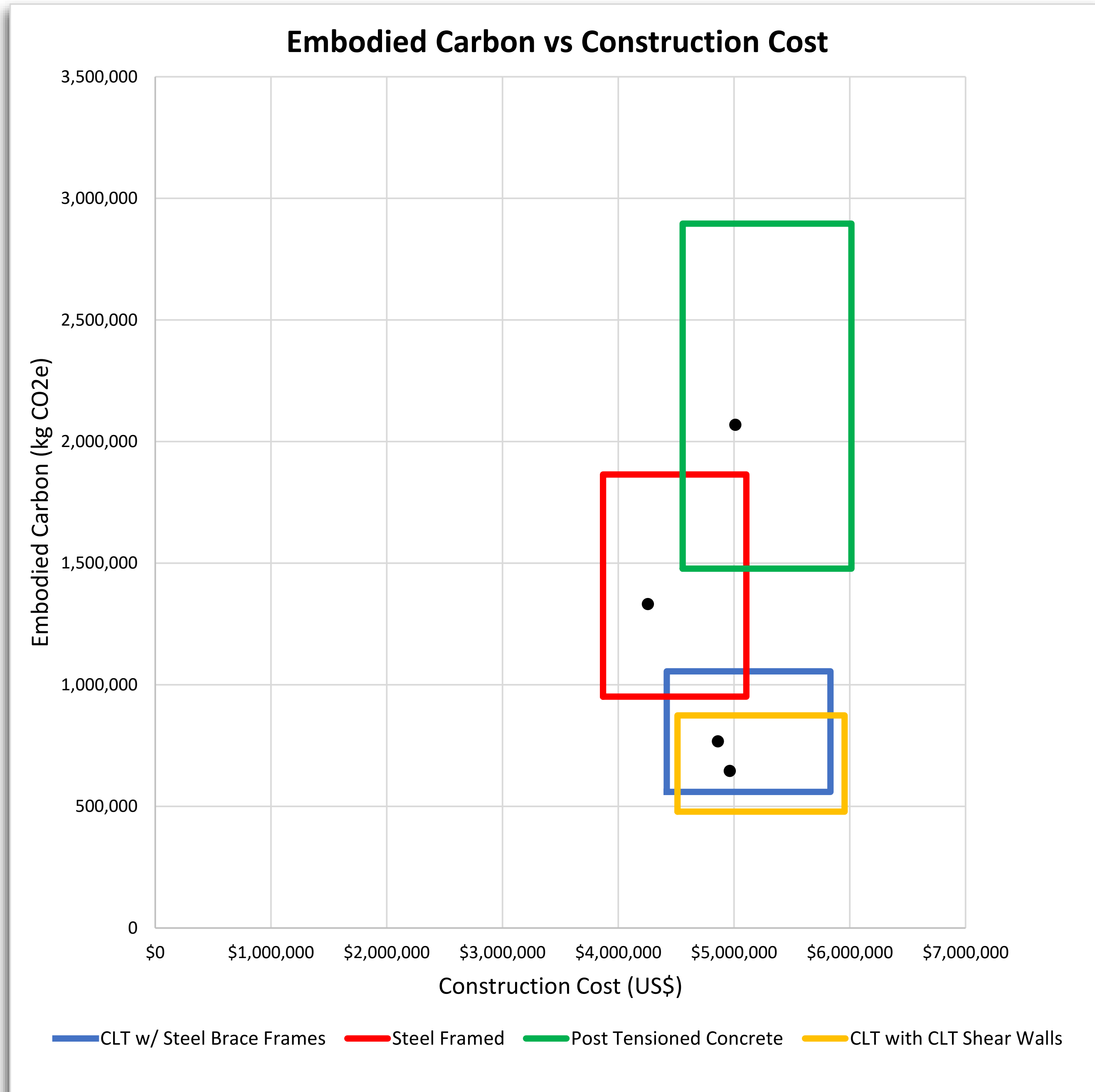
Embodied Carbon Reduction per Building GSF for CLT with CLT Shear Walls vs. Steel Framed =	-13 kg CO2e / GSF

For Every Dollar Spent, Embodied Carbon is Reduced By: Value Equation = kg CO2e Reduction / $ Premium	**-.97 kg CO2e**

The Estimated Price for Reducing a kg of Embodied Carbon:	**$1.03**

CCRVM:	Structural Systems	Analysis Date:	August 30, 2021
Project Owner:	University in Pacific Northwest	Pricing Data Expires:	January 1, 2022
Project Name:	Classroom Building	Pricing Data Status:	Current

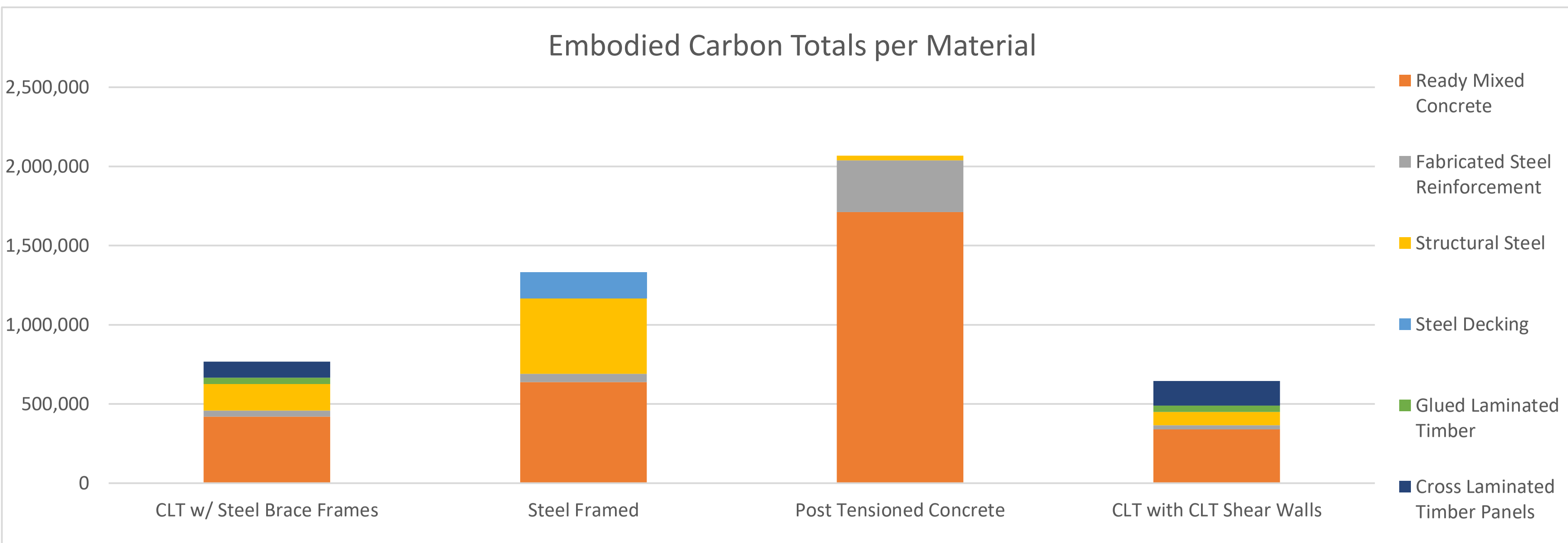
Embodied Carbon Reduction Value Analysis Summary



CCRVM:	Structural Systems	Analysis Date:	August 30, 2021
Project Owner:	University in Pacific Northwest	Pricing Data Expires:	January 1, 2022
Project Name:	Classroom Building	Pricing Data Status:	Current

Material Breakdown Summary

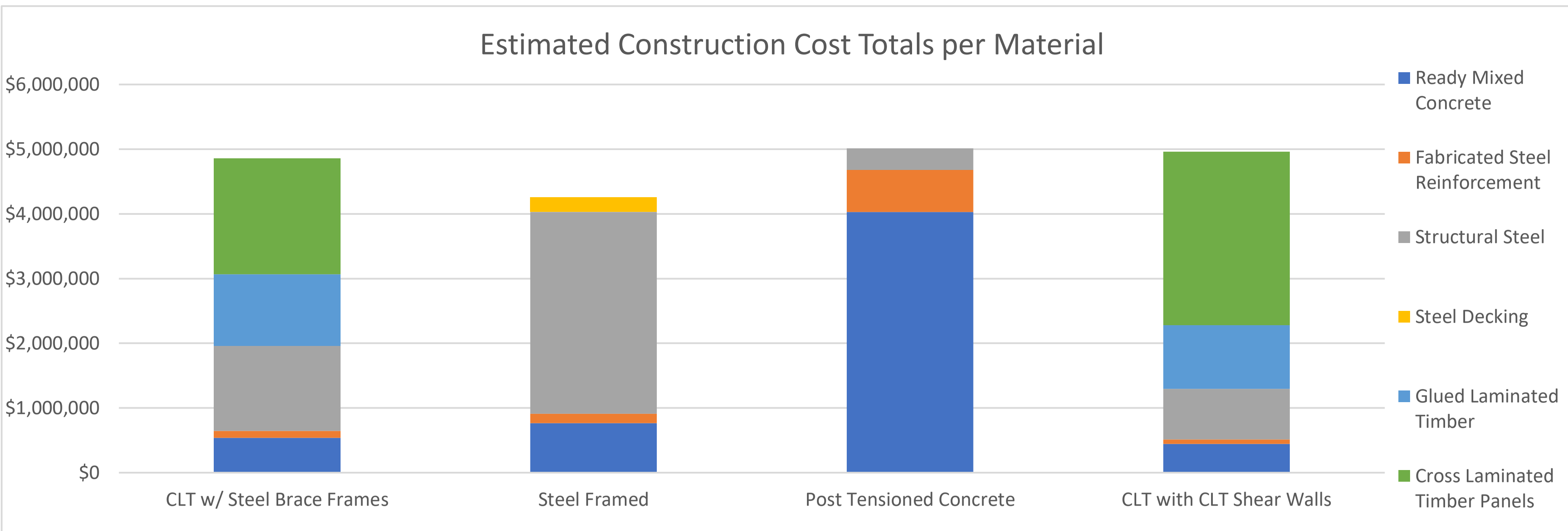
Emobided Carbon Totals per Material				
Description	Alt 1 CLT w/ Steel Brace Frames	Alt 2 Steel Framed	Alt 3 Post Tensioned Concrete	Alt 4 CLT with CLT Shear Walls
Ready Mixed Concrete	420,530	637,855	1,712,337	340,525
Fabricated Steel Reinforcement	37,651	51,952	325,877	25,192
Structural Steel	168,114	476,661	30,458	84,240
Steel Decking	0	165,463	0	0
Glued Laminated Timber	39,896	0	0	39,896
Cross Laminated Timber Panels	101,425	0	0	155,648
Totals	**767,617**	**1,331,933**	**2,068,672**	**645,502**



CCRVM:	Structural Systems	Analysis Date:	August 30, 2021
Project Owner:	University in Pacific Northwest	Pricing Data Expires:	January 1, 2022
Project Name:	Classroom Building	Pricing Data Status:	Current

Material Breakdown Summary

Estimated Construction Cost Totals per Material				
Description	Alt 1 CLT w/ Steel Brace Frames	Alt 2 Steel Framed	Alt 3 Post Tensioned Concrete	Alt 4 CLT with CLT Shear Walls
Ready Mixed Concrete	$540,157	$765,212	$4,029,498	$443,727
Fabricated Steel Reinforcement	$105,982	$146,241	$651,934	$70,913
Structural Steel	$1,311,158	$3,118,260	$330,234	$780,681
Steel Decking	$0	$225,378	$0	$0
Glued Laminated Timber	$1,109,161	$0	$0	$985,921
Cross Laminated Timber Panels	$1,794,210	$0	$0	$2,681,250
Totals	**$4,860,669**	**$4,255,090**	**$5,011,666**	**$4,962,492**



CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Material Quantity Inputs
Alternative 1: CLT w/ Steel Brace Frames

Green Cell = Value to be entered by user | Yellow Cell = Calculated value

Cast in Place Concrete Inputs Required?		Structural Steel Inputs Required?	
Foundations	Yes	Pounds per SF Allowance	Yes
Walls	No	Wide Flange & HSS	No
Columns / Piers	Yes	Miscellaneous Metals	Yes
Slabs	Yes	Steel Deck	No
Elevated Decks	No		
Elevated Beams	No		
Mass Timber Inputs Required?		*Future Inputs*	
Board Feet per SF Allowance	Yes		
Glulam Columns & Beams	No		
Cross Laminted Timber Panels	Yes		

Material Quantity Inputs
Alternative 1: CLT w/ Steel Brace Frames

CIP Foundation Quantities										
Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Quantity	Length - ft	Width - ft	Depth - ft	Volume - cy	lb / cy	Weight - lb	Forms - sf contact area
Spread Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	45.00	7.25	7.25	2.22	194.5	100.0	19,448.1	2,897.1
Continuous Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	1.00	376.00	3.00	1.50	62.7	100.0	6,266.7	1,137.0
Brace Frame Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	1.00	190.00	9.00	5.00	316.7	150.0	47,500.0	1,990.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

CIP Column / Pier Quantities										
Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Quantity	Height - ft	Width - ft	Depth - ft	Volume - cy	lb / cy	Weight - lb	Forms - sf contact area
Column Plinths	4001-5000 psi	0-19% Fly Ash and/or Slag	43.00	2.50	2.50	2.50	24.9	465.0	11,571.2	1,075.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

Material Quantity Inputs
Alternative 1: CLT w/ Steel Brace Frames

CIP Slabs

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Perimeter - ft	Area - sqft	Depth - ft		Volume - cy	lb / sf	Weight - lb	Forms - sf contact area
Topping Slab - Floors (no reinforcing)	3001-4000 psi	0-19% Fly Ash and/or Slag	2,306.00	39,615.0	0.25		366.8	0.00	0.0	576.5
Topping Slab - Roofing (no reinforcing)	3001-4000 psi	0-19% Fly Ash and/or Slag	106.00	650.0	0.50		12.0	0.00	0.0	53.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

Structural Steel Framing Pounds per Square Foot Area Allowances

Description	Steel Quantities (includes connections)		
	Area - sqft	lbs / sf	Weight - lb
Brace Frames & Misc. HSS Support Steel	53,075.0	3.9	204,640.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0

Miscellaneous Metals (list unit of measurement in description line)

Description	Steel Quantities			
	Quantity	lbs. / Qty	Connections %	Weight - lb.
Miscellaneous Metals (lump sum)	1.0	45,620.0	15%	52,463.0
Glulam Beam and Column Connections	812.0	50.0	15%	46,690.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0

Glulam Framing per Square Foot Area Allowances

Description	GLB Quantities			
	Area - sqft	bf / sf	Volume - bf	Volume - cf
Glulam Columns and Beams	53,075	2.3	123,240.2	10,270.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0

Cross Laminated Timber Panels

Description	CLT Panel Quantities		
	Area - sqft	Depth - ft	Volume - cf
CLT Panel, 87mm (3.43")		0.29	0
CLT Panel, 105mm (4.13")		0.34	0

CLT Panel, 139mm (5.47")	13,460	0.46	6,136
CLT Panel, 175mm (6.89")	39,615	0.57	22,746
CLT Panel, 191mm (7.52")		0.63	0
CLT Panel, 245mm (9.65")		0.80	0
CLT Panel, 315mm (12.40")		1.03	0

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Material Quantity Inputs
Alternative 2: Steel Framed

Green Cell = Value to be entered by user   Yellow Cell = Calculated value

Cast in Place Concrete Inputs Required?		Structural Steel Inputs Required?	
Foundations	Yes	Pounds per SF Allowance	Yes
Walls	No	Wide Flange & HSS	No
Columns / Piers	Yes	Miscellaneous Metals	Yes
Slabs	Yes	Steel Deck	Yes
Elevated Decks	No		
Elevated Beams	No		
Mass Timber Inputs Required?		*Future Inputs*	
Board Feet per SF Allowance	No		
Glulam Columns & Beams	No		
Cross Laminted Timber Panels	No		

Material Quantity Inputs
Alternative 2: Steel Framed

CIP Foundation Quantities

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Quantity	Length - ft	Width - ft	Depth - ft	Volume - cy	lb / cy	Weight - lb	Forms - sf contact area
Spread Footings	4001-5000 psi	0-19% Fly Ash and/or Slag	45.00	8.50	8.50	2.50	301.0	90.0	27,093.8	3,825.0
Continuous Footings	4001-5000 psi	0-19% Fly Ash and/or Slag	1.00	376.00	3.00	1.00	41.8	90.0	3,760.0	758.0
Brace Frame Footings	4001-5000 psi	0-19% Fly Ash and/or Slag	1.00	190.00	9.00	5.25	332.5	180.0	59,850.0	2,089.5
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

CIP Column / Pier Quantities

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Quantity	Height - ft	Width - ft	Depth - ft	Volume - cy	lb / cy	Weight - lb	Forms - sf contact area
Column Plinths	5001-6000 psi	0-19% Fly Ash and/or Slag	55.00	2.50	2.50	2.50	31.8	465.0	14,800.3	1,375.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

Material Quantity Inputs
Alternative 2: Steel Framed

CIP Slabs

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Perimeter - ft	Area - sqft	Depth - ft		Volume - cy	lb / sf	Weight - lb	Forms - sf contact area
Topping Slab - Floors	3001-4000 psi	0-19% Fly Ash and/or Slag	2,306.00	39,615.0	0.42		611.3	0.29	11,488.4	960.8
Topping Slab - Roofing (no reinforcing)	3001-4000 psi	0-19% Fly Ash and/or Slag	106.00	650.0	0.50		12.0		0.0	53.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

Structural Steel Framing Pounds per Square Foot Area Allowances

Description	Steel Quantities		
	Area - sqft	lbs / sf	Weight - lb
WF and HSS Steel Framing and Braced Frames	53,075.0	15.4	819,960.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0

Miscellaneous Metals (list unit of measurement in description line)				
Description	Steel Quantities			
	Quantity	lbs. / Qty	Connections %	Weight - lb
Miscellaneous Metals (lump sum)	1.0	36,000.0	15%	41,400.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0

Steel Deck			
Description	Steel Deck Quantities		
	Area - sqft	lbs / sf	Weight - lb
Roof B Deck, 1.5" Deep, 22 Gage		1.90	0.0
Roof B Deck, 1.5" Deep, 20 Gage		2.30	0.0
Roof B Deck, 1.5" Deep, 18 Gage	13,460.0	2.90	39,034.0
Roof B Deck, 1.5" Deep, 16 Gage		3.50	0.0
W3 Floor Deck, 3" Deep, 22 Gage		1.90	0.0
W3 Floor Deck, 3" Deep, 21 Gage		2.10	0.0
W3 Floor Deck, 3" Deep, 20 Gage		2.30	0.0
W3 Floor Deck, 3" Deep, 19 Gage		2.70	0.0
W3 Floor Deck, 3" Deep, 18 Gage	39,615.0	2.90	114,883.5
W3 Floor Deck, 3" Deep, 16 Gage		3.50	0.0

CCRVM:	Structural Systems
Project Owner:	University in Pacific Northwest
Project Name:	Classroom Building

Material Quantity Inputs
Alternative 3: Post Tensioned Concrete

Green Cell	= Value to be entered by user	Yellow Cell	= Calculated value

Cast in Place Concrete Inputs Required?		Structural Steel Inputs Required?	
Foundations	Yes	Pounds per SF Allowance	No
Walls	Yes	Wide Flange & HSS	No
Columns / Piers	Yes	Miscellaneous Metals	Yes
Slabs	No	Steel Deck	No
Elevated Decks	Yes		
Elevated Beams	Yes		
Mass Timber Inputs Required?		*Future Inputs*	
Board Feet per SF Allowance	No		
Glulam Columns & Beams	No		
Cross Laminted Timber Panels	No		

Material Quantity Inputs
Alternative 3: Post Tensioned Concrete

CIP Foundation Quantities

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Quantity	Length - ft	Width - ft	Depth - ft	Volume - cy	lb / cy	Weight - lb	Forms - sf contact area
Spread Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	55.00	12.00	12.00	3.00	880.0	100.0	88,000.0	7,920.0
Continuous Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	1.00	360.00	4.00	2.00	106.7	100.0	10,666.7	1,456.0
Shear Wall Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	1.00	110.00	15.00	6.00	366.7	235.0	86,166.7	1,500.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

CIP Walls Quantities

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Length - ft	Height - ft	Thick - ft		Volume - cy	lb / cy	Weight - lb	Forms - sf contact area
Shear Walls	4001-5000 psi	0-19% Fly Ash and/or Slag	85.00	64.00	1.25		251.9	300.0	75,555.6	10,882.5
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

Material Quantity Inputs
Alternative 3: Post Tensioned Concrete

CIP Column / Pier Quantities

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Quantity	Height - ft	Width - ft	Depth - ft	Volume - cy	lb / cy	Weight - lb	Forms - sf contact area
Concrete Columns	4001-5000 psi	0-19% Fly Ash and/or Slag	55.00	64.00	1.17	1.17	177.4	540.0	95,822.2	16,426.7
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

CIP Elevated Decks

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		P.T. Cable Quantities	
			Perimeter - ft	Area - sqft	Depth - ft		Volume - cy	lb / sf	Weight - lb	lb / sf	Weight - lb
P.T. Floor Decks	5001-6000 psi	0-19% Fly Ash and/or Slag	2,306.00	39,615.0	0.83		1,222.7	3.00	118,845.0	2.00	79,230.0
P.T. Roof Deck	5001-6000 psi	0-19% Fly Ash and/or Slag	620	13,460	0.83		413.8	3.00	40,380.0	2.00	26,920.0
							0.0		0.0		0.0
							0.0		0.0		0.0
							0.0		0.0		0.0
							0.0		0.0		0.0
							0.0		0.0		0.0
							0.0		0.0		0.0
							0.0		0.0		0.0
							0.0		0.0		0.0

Material Quantity Inputs
Alternative 3: Post Tensioned Concrete

CIP Elevated Beam Quantities

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Length - ft	Width - ft	Depth - ft		Volume - cy	lb / cy	Weight - lb	Forms - sf contact area
Concrete Beams	5001-6000 psi	0-19% Fly Ash and/or Slag	120.00	1.25	2.00		11.1	550.0	6,111.1	304.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

Miscellaneous Metals (list unit of measurement in description line)

Description	Steel Quantities			
	Quantity	lbs. / Qty	Connections %	Weight - lb
Miscellaneous Metals (lump sum)	1.0	47,860.0	15%	55,039.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Material Quantity Inputs
Alternative 4: CLT with CLT Shear Walls

Green Cell = Value to be entered by user   Yellow Cell = Calculated value

Cast in Place Concrete Inputs Required?		Structural Steel Inputs Required?	
Foundations	Yes	Pounds per SF Allowance	Yes
Walls	No	Wide Flange & HSS	No
Columns / Piers	Yes	Miscellaneous Metals	Yes
Slabs	Yes	Steel Deck	No
Elevated Decks	No		
Elevated Beams	No		
Mass Timber Inputs Required?		*Future Inputs*	
Board Feet per SF Allowance	Yes		
Glulam Columns & Beams	No		
Cross Laminted Timber Panels	Yes		

Material Quantity Inputs
Alternative 4: CLT with CLT Shear Walls

CIP Foundation Quantities

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Quantity	Length - ft	Width - ft	Depth - ft	Volume - cy	lb / cy	Weight - lb	Forms - sf contact area
Spread Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	45.00	7.25	7.25	2.22	194.5	100.0	19,448.1	2,897.1
Continuous Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	1.00	376.00	3.00	1.50	62.7	100.0	6,266.7	1,137.0
Shear Wall Footings	3001-4000 psi	0-19% Fly Ash and/or Slag	1.00	350.00	5.00	2.00	129.6	150.0	19,444.4	1,420.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

CIP Column / Pier Quantities

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Quantity	Height - ft	Width - ft	Depth - ft	Volume - cy	lb / cy	Weight - lb	Forms - sf contact area
Column Plinths	4001-5000 psi	0-19% Fly Ash and/or Slag	43.00	2.50	2.50	2.50	24.9	465.0	11,571.2	1,075.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

Material Quantity Inputs

Alternative 4: CLT with CLT Shear Walls

CIP Slabs

Description	Compressive Strength Range	Suppl. Cementing Materials. Range (%)	Concrete Quantities					Rebar Quantities		Formwork Quantities
			Perimeter - ft	Area - sqft	Depth - ft		Volume - cy	lb / sf	Weight - lb	Forms - sf contact area
Topping Slab - Floors (no reinforcing)	3001-4000 psi	0-19% Fly Ash and/or Slag	2,306.00	39,615.0	0.25		366.8		0.0	576.5
Topping Slab - Roofing (no reinforcing)	3001-4000 psi	0-19% Fly Ash and/or Slag	106.00	650.0	0.50		12.0		0.0	53.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0
							0.0		0.0	0.0

Structural Steel Framing Pounds per Square Foot Area Allowances

Description	Steel Quantities		
	Area - sqft	lbs / sf	Weight - lb
Misc. HSS Support Steel	53,075.0	1.0	53,075.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0
			0.0

Miscellaneous Metals (list unit of measurement in description line)				
Description	Steel Quantities			
	Quantity	lbs. / Qty	Connections %	Weight - lb
Miscellaneous Metals (lump sum)	1.0	45,620.0	15%	52,463.0
Glulam Beam and Column Connections	812.0	50.0	15%	46,690.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0
			15%	0.0

Glulam Framing per Square Foot Area Allowances				
Description	GLB Quantities			
	Area - sqft	bf / sf	Volume - bf	Volume - cf
Glulam Columns and Beams	53,075	2.3	123,240.2	10,270.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0
			0.0	0.0

Cross Laminated Timber Panels			
Description	CLT Panel Quantities		
	Area - sqft	Depth - ft	Volume - cf
CLT Panel, 87mm (3.43")		0.29	0
CLT Panel, 105mm (4.13")		0.34	0
CLT Panel, 139mm (5.47")	13,460	0.46	6,136
CLT Panel, 175mm (6.89")	39,615	0.57	22,746
CLT Panel, 191mm (7.52")		0.63	0
CLT Panel, 245mm (9.65")	19,200	0.80	15,440
CLT Panel, 315mm (12.40")		1.03	0

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Cost Estimation Details

Alternative 1: CLT w/ Steel Brace Frames

Green Cell = Value to be entered by user   Yellow Cell = Calculated value

Cast in Place Concrete Pricing (pricing per cubic yard automatically adjusts for mix design and includes pumping)

Description	Concrete Pricing		Reinforcing Pricing		P.T. Cable Pricing		Formwork Pricing		Extension	Check	
	Quantity - cy	$ / CY	Quantity - lb	$ / lb	Quantity - lb	$ / SF	Quantity - sfca	$ / SF	Total $	$	Unit
Foundations	573.8	$234.00	73,214.8	$1.25			6,024.1	$27.00	$388,442	$676.95	cy
Walls	0.0		0.0	$1.25			0.0	$23.00	$0		sf
Coumns / Piers	24.9	$228.00	11,571.2	$1.25			1,075.0	$30.00	$52,388	$2,105.25	cy
Slabs (includes finishing)	378.8	$522.00	0.0	$1.25			629.5	$12.00	$205,310	$5.10	sf
Elevated Decks (includes finishing)	0.0		0.0	$1.25	0.0	$1.80	0.0	$18.00	$0		sf
Elevated Beams	0.0		0.0	$1.25			0.0	$29.00	$0		cy
Subtotal			**$105,982**						**$646,139**		

Structural Steel Pricing

Description	Steel Shapes Pricing		Extension	Check	
	Quantity - lb	$ / lb	Total $	$	Unit
Steel Columns, Beams, Angles, Etc…	204,640.0	$3.50	$716,240	$13.49	sf of structure
Misc. Metals	99,153.0	$6.00	$594,918	$11.21	sf of structure
Subtotal			**$1,311,158**		

Cost Estimation Details
Alternative 1: CLT w/ Steel Brace Frames

Steel Deck Pricing			
Description	Metal Deck Pricing		Extension
	Quantity - sf	$ / sf	Total $
Roof B Deck, 1.5" Deep, 22 Gage	0.0	$3.00	$0
Roof B Deck, 1.5" Deep, 20 Gage	0.0	$3.25	$0
Roof B Deck, 1.5" Deep, 18 Gage	0.0	$3.50	$0
Roof B Deck, 1.5" Deep, 16 Gage	0.0	$3.75	$0
W3 Floor Deck, 3" Deep, 22 Gage	0.0	$3.50	$0
W3 Floor Deck, 3" Deep, 21 Gage	0.0	$3.75	$0
W3 Floor Deck, 3" Deep, 20 Gage	0.0	$4.00	$0
W3 Floor Deck, 3" Deep, 19 Gage	0.0	$4.25	$0
W3 Floor Deck, 3" Deep, 18 Gage	0.0	$4.50	$0
W3 Floor Deck, 3" Deep, 16 Gage	0.0	$4.75	$0
Subtotal			**$0**

Glulam Framing Pricing					
Description	Glulam Pricing		Extension	Check	
	Quantity - bf	$ / bf	Total $	$	Unit
Glulam Columns and Beams	123,240.2	$9.00	$1,109,161	$20.90	sf of structure
Subtotal			**$1,109,161**		

Cross Laminated Timber Panel Pricing			
Description	CLT Pricing		Extension
	Quantity - sf	$ / sf	Total $
CLT Panel, 87mm (3.43")	0.0	$22.00	$0
CLT Panel, 105mm (4.13")	0.0	$25.30	$0
CLT Panel, 139mm (5.47")	13,460.0	$29.70	$399,762
CLT Panel, 175mm (6.89")	39,615.0	$35.20	$1,394,448
CLT Panel, 191mm (7.52")	0.0	$39.60	$0
CLT Panel, 245mm (9.65")	0.0	$46.20	$0
CLT Panel, 315mm (12.40")	0.0	$55.00	$0
Subtotal			**$1,794,210**

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Cost Estimation Details

Alternative 2: Steel Framed

Green Cell = Value to be entered by user

Yellow Cell = Calculated value

Cast in Place Concrete Pricing (pricing per cubic yard automatically adjusts for mix design and includes pumping)

Description	Concrete Pricing		Reinforcing Pricing		P.T. Cable Pricing		Formwork Pricing		Extension	Check	
	Quantity - cy	$ / CY	Quantity - lb	$ / lb	Quantity - lb	$ / SF	Quantity - sfca	$ / SF	Total $	$	Unit
Foundations	675.3	$240.00	90,703.8	$1.25			6,672.5	$27.00	$455,614	$674.66	cy
Walls	0.0		0.0	$1.25			0.0	$23.00	$0		sf
Coumns / Piers	31.8	$234.00	14,800.3	$1.25			1,375.0	$30.00	$67,198	$2,111.25	cy
Slabs (float finished)	623.4	$522.00	11,488.4	$1.25			1,013.8	$8.50	$348,382	$8.65	sf
Elevated Decks (float finished)	0.0		0.0	$1.25	0.0	$1.80	0.0	$18.00	$0		sf
Elevated Beams	0.0		0.0	$1.25			0.0	$29.00	$0		cy
Subtotal			**$146,241**						**$871,194**		

Structural Steel Pricing

Description	Steel Shapes Pricing		Extension	Check	
	Quantity - lb	$ / lb	Total $	$	Unit
Steel Columns, Beams, Angles, Etc…	819,960.0	$3.50	$2,869,860	$54.07	sf of structure
Misc. Metals	41,400.0	$6.00	$248,400	$4.68	sf of structure
Subtotal			**$3,118,260**		

Steel Deck Pricing

Description	Metal Deck Pricing		Extension
	Quantity - sf	$ / sf	Total $
Roof B Deck, 1.5" Deep, 22 Gage	0.0	$3.00	$0
Roof B Deck, 1.5" Deep, 20 Gage	0.0	$3.25	$0
Roof B Deck, 1.5" Deep, 18 Gage	13,460.0	$3.50	$47,110
Roof B Deck, 1.5" Deep, 16 Gage	0.0	$3.75	$0
W3 Floor Deck, 3" Deep, 22 Gage	0.0	$3.50	$0
W3 Floor Deck, 3" Deep, 21 Gage	0.0	$3.75	$0
W3 Floor Deck, 3" Deep, 20 Gage	0.0	$4.00	$0
W3 Floor Deck, 3" Deep, 19 Gage	0.0	$4.25	$0
W3 Floor Deck, 3" Deep, 18 Gage	39,615.0	$4.50	$178,268
W3 Floor Deck, 3" Deep, 16 Gage	0.0	$4.75	$0
Subtotal			**$225,378**

Glulam Framing Pricing

Description	Steel Shapes Pricing		Extension	Check	
	Quantity - bf	$ / lb	Total $	$	Unit
Glulam Columns and Beams	0.0	$8.00	$0		sf of structure
Subtotal			**$0**		

Cross Laminated Timber Panel Pricing

Description	CLT Pricing		Extension
	Quantity - sf	$ / sf	Total $
CLT Panel, 87mm (3.43")	0.0	$22.00	$0
CLT Panel, 105mm (4.13")	0.0	$25.30	$0
CLT Panel, 139mm (5.47")	0.0	$29.70	$0
CLT Panel, 175mm (6.89")	0.0	$35.20	$0
CLT Panel, 191mm (7.52")	0.0	$39.60	$0
CLT Panel, 245mm (9.65")	0.0	$46.20	$0
CLT Panel, 315mm (12.40")	0.0	$55.00	$0
Subtotal			**$0**

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Cost Estimation Details

Alternative 3: Post Tensioned Concrete

Green Cell = Value to be entered by user | Yellow Cell = Calculated value

Cast in Place Concrete Pricing (pricing per cubic yard automatically adjusts for mix design and includes pumping)											
Description	Concrete Pricing		Reinforcing Pricing		P.T. Cable Pricing		Formwork Pricing		Extension	Check	
	Quantity - cy	$ / CY	Quantity - lb	$ / lb	Quantity - lb	$ / SF	Quantity - sfca	$ / SF	Total $	$	Unit
Foundations	1,353.3	$234.00	184,833.3	$1.25			10,876.0	$27.00	$841,374	$621.70	cy
Walls	251.9	$228.00	75,555.6	$1.25			10,882.5	$23.00	$402,164	$73.93	sf
Coumns / Piers	177.4	$228.00	95,822.2	$1.25			16,426.7	$30.00	$653,036	$3,680.14	cy
Slabs (float finished)	0.0		0.0	$1.25			0.0	$8.50	$0		sf
Elevated Decks (float finished)	1,636.5	$534.00	159,225.0	$1.25	106,150.0	$1.80	53,075.0	$18.00	$2,219,319	$41.81	sf
Elevated Beams	11.1	$282.00	6,111.1	$1.25			304.0	$29.00	$19,588	$1,762.94	cy
Subtotal			**$651,934**						**$4,135,481**		

Structural Steel Pricing					
Description	Steel Shapes Pricing		Extension	Check	
	Quantity - lb	$ / lb	Total $	$	Unit
Steel Columns, Beams, Angles, Etc...	0.0	$3.50	$0	$0.00	sf of structure
Misc. Metals	55,039.0	$6.00	$330,234	$6.22	sf of structure
Subtotal			**$330,234**		

Steel Deck Pricing			
Description	Metal Deck Pricing		Extension
	Quantity - sf	$ / sf	Total $
Roof B Deck, 1.5" Deep, 22 Gage	0.0	$3.00	$0
Roof B Deck, 1.5" Deep, 20 Gage	0.0	$3.25	$0
Roof B Deck, 1.5" Deep, 18 Gage	0.0	$3.50	$0
Roof B Deck, 1.5" Deep, 16 Gage	0.0	$3.75	$0
W3 Floor Deck, 3" Deep, 22 Gage	0.0	$3.50	$0
W3 Floor Deck, 3" Deep, 21 Gage	0.0	$3.75	$0
W3 Floor Deck, 3" Deep, 20 Gage	0.0	$4.00	$0
W3 Floor Deck, 3" Deep, 19 Gage	0.0	$4.25	$0
W3 Floor Deck, 3" Deep, 18 Gage	0.0	$4.50	$0
W3 Floor Deck, 3" Deep, 16 Gage	0.0	$4.75	$0
Subtotal			**$0**

Glulam Framing Pricing					
Description	Steel Shapes Pricing		Extension	Check	
	Quantity - bf	$ / lb	Total $	$	Unit
Glulam Columns and Beams	0.0	$8.00	$0		sf of structure
Subtotal			**$0**		

Cross Laminated Timber Panel Pricing			
Description	CLT Pricing		Extension
	Quantity - sf	$ / sf	Total $
CLT Panel, 87mm (3.43")	0.0	$22.00	$0
CLT Panel, 105mm (4.13")	0.0	$25.30	$0
CLT Panel, 139mm (5.47")	0.0	$29.70	$0
CLT Panel, 175mm (6.89")	0.0	$35.20	$0
CLT Panel, 191mm (7.52")	0.0	$39.60	$0
CLT Panel, 245mm (9.65")	0.0	$46.20	$0
CLT Panel, 315mm (12.40")	0.0	$55.00	$0
Subtotal			**$0**

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Cost Estimation Details

Alternative 4: CLT with CLT Shear Walls

Green Cell = Value to be entered by user   Yellow Cell = Calculated value

Cast in Place Concrete Pricing (pricing per cubic yard automatically adjusts for mix design and includes pumping)

Description	Concrete Pricing		Reinforcing Pricing		P.T. Cable Pricing		Formwork Pricing		Extension	Check	
	Quantity - cy	$ / CY	Quantity - lb	$ / lb	Quantity - lb	$ / SF	Quantity - sfca	$ / SF	Total $	$	Unit
Foundations	386.8	$234.00	45,159.2	$1.25			5,454.1	$27.00	$294,216	$760.68	cy
Walls	0.0		0.0	$1.25			0.0	$23.00	$0		sf
Coumns / Piers	24.9	$228.00	11,571.2	$1.25			1,075.0	$30.00	$52,388	$2,105.25	cy
Slabs (float finished)	378.8	$522.00	0.0	$1.25			629.5	$8.50	$203,107	5.04424645	sf
Elevated Decks (float finished)	0.0		0.0	$1.25	0.0	$1.80	0.0	$18.00	$0		sf
Elevated Beams	0.0		0.0	$1.25			0.0	$29.00	$0		cy
Subtotal			**$70,913**						**$549,710**		

Structural Steel Pricing

Description	Steel Shapes Pricing		Extension	Check	
	Quantity - lb	$ / lb	Total $	$	Unit
Steel Columns, Beams, Angles, Etc…	53,075.0	$3.50	$185,763	$3.50	sf of structure
Misc. Metals	99,153.0	$6.00	$594,918	$11.21	sf of structure
Subtotal			**$780,681**		

Cost Estimation Details
Alternative 4: CLT with CLT Shear Walls

Steel Deck Pricing			
Description	Metal Deck Pricing		Extension
	Quantity - sf	$ / sf	Total $
Roof B Deck, 1.5" Deep, 22 Gage	0.0	$3.00	$0
Roof B Deck, 1.5" Deep, 20 Gage	0.0	$3.25	$0
Roof B Deck, 1.5" Deep, 18 Gage	0.0	$3.50	$0
Roof B Deck, 1.5" Deep, 16 Gage	0.0	$3.75	$0
W3 Floor Deck, 3" Deep, 22 Gage	0.0	$3.50	$0
W3 Floor Deck, 3" Deep, 21 Gage	0.0	$3.75	$0
W3 Floor Deck, 3" Deep, 20 Gage	0.0	$4.00	$0
W3 Floor Deck, 3" Deep, 19 Gage	0.0	$4.25	$0
W3 Floor Deck, 3" Deep, 18 Gage	0.0	$4.50	$0
W3 Floor Deck, 3" Deep, 16 Gage	0.0	$4.75	$0
Subtotal			**$0**

Glulam Framing Pricing					
Description	Steel Shapes Pricing		Extension	Check	
	Quantity - bf	$ / lb	Total $	$	Unit
Glulam Columns and Beams	123,240.2	$8.00	$985,921	$13.64	sf of structure
Subtotal			**$985,921**		

Cross Laminated Timber Panel Pricing			
Description	CLT Pricing		Extension
	Quantity - sf	$ / sf	Total $
CLT Panel, 87mm (3.43")	0.0	$22.00	$0
CLT Panel, 105mm (4.13")	0.0	$25.30	$0
CLT Panel, 139mm (5.47")	13,460.0	$29.70	$399,762
CLT Panel, 175mm (6.89")	39,615.0	$35.20	$1,394,448
CLT Panel, 191mm (7.52")	0.0	$39.60	$0
CLT Panel, 245mm (9.65")	19,200.0	$46.20	$887,040
CLT Panel, 315mm (12.40")	0.0	$55.00	$0
Subtotal			**$2,681,250**

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Life Cycle Analysis by EPD Details
Alternative 1: CLT w/ Steel Brace Frames

Green Cell = Value to be entered by user
Yellow Cell = Calculated value

Ready Mixed Concrete Embodied Carbon (kg CO2 automatically adjusts for different combination of mix designs)

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - cy	Qty Conversion- m3	kg CO2 / m3	kg CO2 Total	Range of Values
Concrete Structure	977.5	747.4	562.7	**420,530.5**	-40% to +40%

Fabricated Steel Reinforcement Embodied Carbon (P.T. cable quantity included at 2x)

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Total	Range of Values
Rebar and P.T. Cable Reinforcing	84,786.0	38.46	979.0	**37,650.6**	-40% to +40%

Structural Steel Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Total	Range of Values
Steel Columns, Beams, Angles, Etc…	303,793.0	137.80	1,220.0	**168,113.7**	-40% to +40%

Steel Deck Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Total	Range of Values
Floor and Roof Steel Decking	0.0	0.00	2,370.0	**0.0**	-40% to +40%

LCA by EPD Details

Alternative 1: CLT w/ Steel Brace Frames

Glulam Framing Embodied Carbon					
Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - cf	Qty Conversion- m3	kg CO2 / m3	kg CO2 Total	Range of Values
Beams and Columns	10,270.0	290.81	137.2	**39,896.4**	-40% to +40%

Cross Laminated Timber Panel Embodied Carbon					
Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Product Specific
	Quantity - cf	Qty Conversion- m3	kg CO2 / m3	kg CO2 Total	Range of Values
CLT Panels	28,881.1	817.81	124.0	**101,425.4**	-21% to +21%

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Life Cycle Analysis by EPD Details
Alternative 2: Steel Framed

Green Cell = Value to be entered by user   Yellow Cell = Calculated value

Ready Mixed Concrete Embodied Carbon (kg CO2 automatically adjusts for different combination of mix designs)					
Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - cy	Qty Conversion- m3	kg CO2 / m3	kg CO2 Ext.	Range of Values
Concrete Structure	1,330.5	1017.2	627.1	**637,855.5**	-40% to +40%

Fabricated Steel Reinforcement Embodied Carbon (P.T. cable quantity included at 2x)					
Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Ext.	Range of Values
Rebar and P.T. Cable Reinforcing	116,992.4	53.07	979.0	**51,952.4**	-40% to +40%

Structural Steel Embodied Carbon					
Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Ext.	Range of Values
Steel Columns, Beams, Angles, Etc…	861,360.0	390.71	1,220.0	**476,661.3**	-40% to +40%

Steel Deck Embodied Carbon					
Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Ext.	Range of Values
Floor and Roof Steel Decking	153,917.5	69.82	2,370.0	**165,463.3**	-40% to +40%

LCA by EPD Details

Alternative 2: Steel Framed

Glulam Framing Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - cf	Qty Conversion- m3	kg CO_2 / m3	kg CO_2 Ext.	Range of Values
Beams and Columns	0.0	0.00	137.2	**0.0**	-40% to +40%

Cross Laminated Timber Panel Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Product Specific
	Quantity - cf	Qty Conversion- m3	kg CO_2 / m3	kg CO_2 Ext.	Range of Values
CLT Panels	0.0	0.00	124.0	**0.0**	-21% to +21%

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Life Cycle Analysis by EPD Details
Alternative 3: Post Tensioned Concrete

Green Cell = Value to be entered by user   Yellow Cell = Calculated value

Ready Mixed Concrete Embodied Carbon (kg CO2 automatically adjusts for different combination of mix designs)

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - cy	Qty Conversion- m3	kg CO2 / m3	kg CO2 Ext.	Range of Values
Concrete Structure	3,430.2	2622.5	652.9	**1,712,337.4**	-40% to +40%

Fabricated Steel Reinforcement Embodied Carbon (P.T. cable quantity included at 2x)

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Ext.	Range of Values
Rebar and P.T. Cable Reinforcing	733,847.2	332.87	979.0	**325,877.0**	-40% to +40%

Structural Steel Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Ext.	Range of Values
Steel Columns, Beams, Angles, Etc…	55,039.0	24.97	1,220.0	**30,457.6**	-40% to +40%

Steel Deck Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Ext.	Range of Values
Floor and Roof Steel Decking	0.0	0.00	2,370.0	**0.0**	-40% to +40%

LCA by EPD Details

Alternative 3: Post Tensioned Concrete

Glulam Framing Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - cf	Qty Conversion- m3	kg CO2 / m3	kg CO2 Ext.	Range of Values
Beams and Columns	0.0	0.00	137.2	**0.0**	-40% to +40%

Cross Laminated Timber Panel Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Product Specific
	Quantity - cf	Qty Conversion- m3	kg CO2 / m3	kg CO2 Ext.	Range of Values
CLT Panels	0.0	0.00	124.0	**0.0**	-21% to +21%

CCRVM: Structural Systems
Project Owner: University in Pacific Northwest
Project Name: Classroom Building

Life Cycle Analysis by EPD Details
Alternative 4: CLT with CLT Shear Walls

Green Cell	= Value to be entered by user	Yellow Cell	= Calculated value

Ready Mixed Concrete Embodied Carbon (kg CO2 automatically adjusts for different combination of mix designs)

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - cy	Qty Conversion- m3	kg CO2 / m3	kg CO2 Ext.	Range of Values
Concrete Structure	790.5	604.4	563.4	**340,525.4**	-40% to +40%

Fabricated Steel Reinforcement Embodied Carbon (P.T. cable quantity included at 2x)

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Ext.	Range of Values
Rebar and P.T. Cable Reinforcing	56,730.4	25.73	979.0	**25,192.1**	-40% to +40%

Structural Steel Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Ext.	Range of Values
Steel Columns, Beams, Angles, Etc…	152,228.0	69.05	1,220.0	**84,240.3**	-40% to +40%

Steel Deck Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - lb*	Qty Conversion- mt	kg CO2 / mt	kg CO2 Ext.	Range of Values
Floor and Roof Steel Decking	0.0	0.00	2,370.0	**0.0**	-40% to +40%

LCA by EPD Details

Alternative 4: CLT with CLT Shear Walls

Glulam Framing Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Industry Average
	Quantity - cf	Qty Conversion- m3	kg CO2 / m3	kg CO2 Ext.	Range of Values
Beams and Columns	10,270.0	290.81	137.2	**39,896.4**	-40% to +40%

Cross Laminated Timber Panel Embodied Carbon

Description	Input Quantities	GWP Values (Product Stage Embodied Carbon)			EPD Type: Product Specific
	Quantity - cf	Qty Conversion- m3	kg CO2 / m3	kg CO2 Ext.	Range of Values
CLT Panels	44,321.1	1255.02	124.0	**155,647.9**	-21% to +21%