Reduced-Carbon Envelope Systems for More Sustainable Industrial Properties: A Cost Analysis of Reducing Greenhouse Gas Emissions

by

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ABSTRACT

Building operations and the construction industry account for 49% of global carbon emissions. Although different approaches have tried to lower the emissions of building operations, there have not been many initiatives to reduce the carbon emitted in construction. Currently, the embodied carbon of buildings in construction is lower than the operational carbon over their useful life. Nevertheless, if not enough attention is directed toward making the construction industry more sustainable, embodied carbon is expected to become the largest environmental hazard in real estate.

Driven by growth in e-commerce and international problems with supply chains, industrial buildings have experienced the largest increase in demand the past few years compared to other property types. Yet, initiatives to make construction systems for industrial buildings more sustainable are not well developed, and thus these initiatives are not commonly used or known.

This report aims to analyze reduced-carbon materials and systems currently used in industrial construction. A comparison of carbon emissions and prices will be studied to set costs for every ton of CO_2 not released into the environment. The report will apply a case study to approximate a real-life scenario and thus attempt to understand how much more expensive it is to build reduced-carbon industrial structures. The goal of this thesis is to understand how clear the path to a much needed more sustainable industrial building market is.

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1.1. Purpose and Motivation

The creation of new materials out of raw substances such as cement, steel, or plastic, and their transformation into objects, is responsible for 31% of the current greenhouse gas emissions on Earth. A comparison of this figure to rates in other sectors, such as energy consumption (responsible for 27% of greenhouse gas emissions), agriculture and farming (19%), transportation (16%), and thermoregulation (7%), shows clearly that creating materials and objects is the largest emissions producer among other human activities (Dolan, 2021).

Why does this matter? Greenhouse gases absorb and trap heat, just like the glass walls of a greenhouse, hence their name. This does not make them intrinsically bad. Thanks to greenhouse gases, enough heat has remained in the atmosphere to enable the human species to develop and inhabit the Earth.

Nevertheless, greenhouse gas emissions have increased drastically since 1850 due to activities like burning fossil fuels. Greenhouse gases can stay in the atmosphere for 300 to 10,000 years (Buis, 2019). This leads to increasing temperatures and might ultimately make the earth unlivable. In the two graphs below, we can see a comparison of global carbon dioxide emissions and changes in the global average temperature. The graphs show a strong relationship between global carbon dioxide emissions and the rise of global average temperatures.

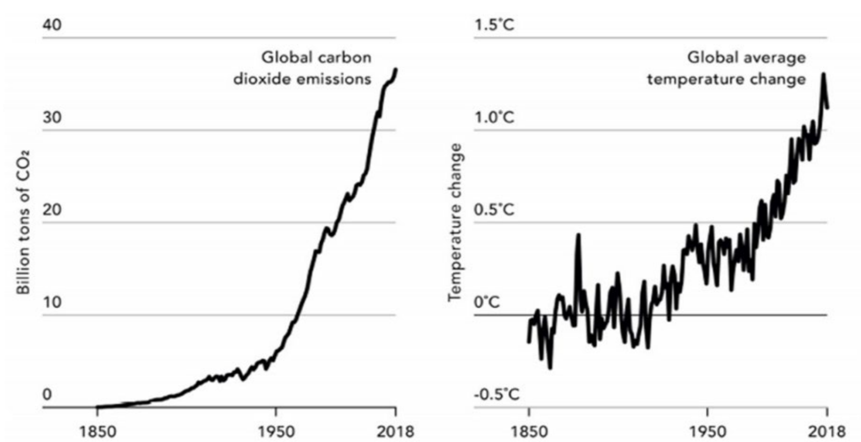

Figure 1- Global Carbon Emissions and Temperature Change (Berkeley Earth, 2019; As cited in Lakoff, 2021)

A rise of 1.5 degrees Celsius (2.7 degrees Fahrenheit) is projected for 2050 and a rise of 2–4 degrees Celsius (3.6–7.2 degrees Fahrenheit) for the end of the century (Wisconsin DNR, n.d.). This might not seem like a big change, but it is a significant one. The average temperature of the Earth in the last Ice Age was only 6 degrees Celsius below today's average temperature. In the age of dinosaurs, when the Earth was only warmer by 4 degrees Celsius, there were crocodiles living above the Arctic Circle (Gates, 2021).

The projected increase in the Earth's average temperature will make it much harder for humans and other species to survive. Hurricanes and storms can severely affect cities and communities.

Recovering from them requires resources necessary for the continued development of the affected societies. One striking example is Hurricane Maria, which set Puerto Rico's infrastructure back by 20 years (Gates, 2021).

An increase in temperature also causes extensive droughts and wildfires, which primarily affect agricultural communities. In addition, the melting of polar ice and expansion of seawater will cause sea levels to rise.

There is no doubt that we need to work on solutions to stop climate change. With that in mind, this thesis will address the need for reduced-carbon construction systems. The next sections in this introduction will discuss the importance of the construction industry in addressing climate change along with increased attention to the relevance of industrial properties in real estate. The end of the first chapter will offer key definitions and explain the research methodology and thesis structure.

1.2. Impact of the Construction Industry on Climate Change

As mentioned at the beginning of the report, the creation of new materials and objects is responsible for 31% of the greenhouse gases emitted by human activities. Bill Gates compared greenhouse gas emissions among human activities in his book *How to Avoid a Climate Disaster*, using data taken from the U.S. Energy Information Administration. This graph is the result:

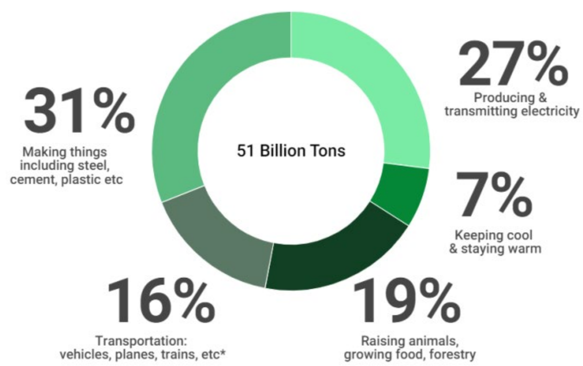

Figure 2 - Carbon Emissions by Activities (Dolan, 2021)

Carbon emissions from buildings can be divided into two types: embodied carbon and operational carbon. Operational greenhouse gas emissions come from energy usage, HVAC systems, and gas appliances, among other sources. Embodied carbon refers to greenhouse gas emissions from building construction and the estimated disposal of building materials. In the construction process, manufacturing, transportation, and assemblage of materials are included.

Currently, operational carbon of a building over its useful life is on average higher than embodied carbon. In the future, thanks to the efforts to reduce operational emissions and create cleaner energy, the World Green Building Council says embodied carbon could have a higher percentage of a building's footprint (Yee, 2021).

In the graph below we can see projections of the distribution of a building's footprint between operational carbon and embodied carbon over a 20-year time frame. This is partly the result of progress in how we operate buildings, but it also shows a lack of effective efforts to reduce embodied carbon in the construction industry.

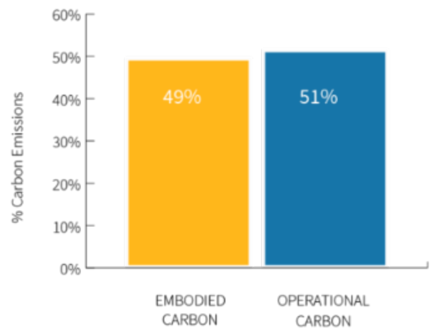

Figure 3 - Total Carbon Emissions of Global New Construction from 2020-2050 (Yee, 2021)

It is expected that the stock of built square feet will double by 2060 (Yee, 2021). Today, if divided by sectors, the construction industry accounts for approximately 50% of global carbon emissions. In the chart below we can see the impact of the real estate industry on climate change and the vital role it can play in efforts to slow it down.

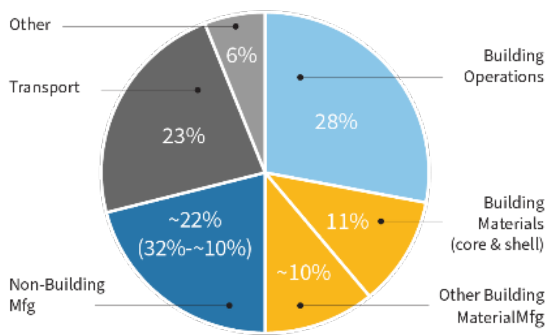

Figure 4 - Global Emissions by Sector (Carbon Leadership Forum, 2022

The real estate industry has made some progress in decreasing the emissions from operations of new buildings. Now the focus needs to shift to how we decarbonize our existing building stock and how we build. Advances in research in this area have been mostly ignored by manufacturing and construction companies. Implementing new construction methods can be seen as a risk because they are untested. If this trend continues, efforts to slow down climate change in other sectors will not be sufficient.

1.3. Growth and Relevance of the Industrial Market

In 2021, the industrial real estate market faced an unprecedented increase in demand. The growth in e-commerce, driven by COVID-19, passed from 16.2% in Q1 2020 to 21.6% in Q2 of that same year. Since then, it has stabilized above pre-pandemic levels at 20% (CBRE, 2022b).

Industrial rented space is expected to continue growing due to a projected expansion in online sales. Demand is driven by the necessity of accommodating supply sourcing, inventory control, and customer reach. While the general real estate market faces volatility caused by a recessionary environment, the volume and source of online consumption will continue to stabilize the industrial market.

The graph below shows that even though there was a decline in peak demand, the rate of industrial real estate demand is still higher than it was before the pandemic began. Supply is starting to keep up with demand after a couple of years of being insufficient. It might seem that demand is going down but this obeys the cyclicality of real estate markets. Supply will have to slow down before demand exceeds it again. Nevertheless, the increase in e-commerce and the new needs created by it indicate we probably will not get close to pre-pandemic levels of demand or supply.

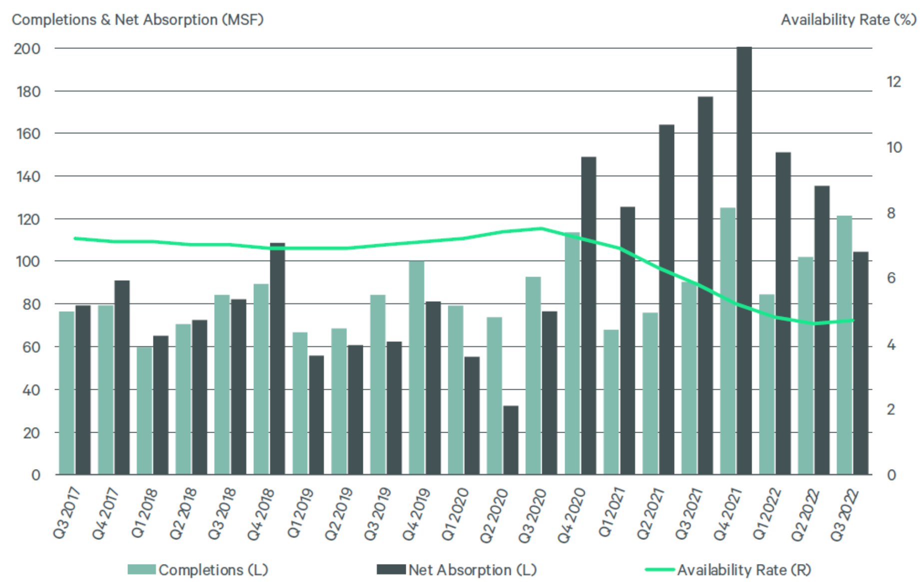

Figure 5 - U.S. Industrial Completions, Net Absorption, and Availability Rate (CBRE, 2022c)

Additionally, the disruption in the supply chain has also severely impacted the demand for industrial real estate. Now, companies need to have a “safety stock” inventory. Domestic freight costs increased by over 40% in 2021, and shipping goods via ocean freight increased charges by more than 200% (CBRE, 2022a). These elevated costs might remain at these levels for the foreseeable future.

In the graph below, we can see the U.S. supply chain indicators. Industrial production and consumer spending are rising and continuing to increase the demand for industrial square feet, but the highest driver of the increase in demand is business inventories for e-retail and distribution.

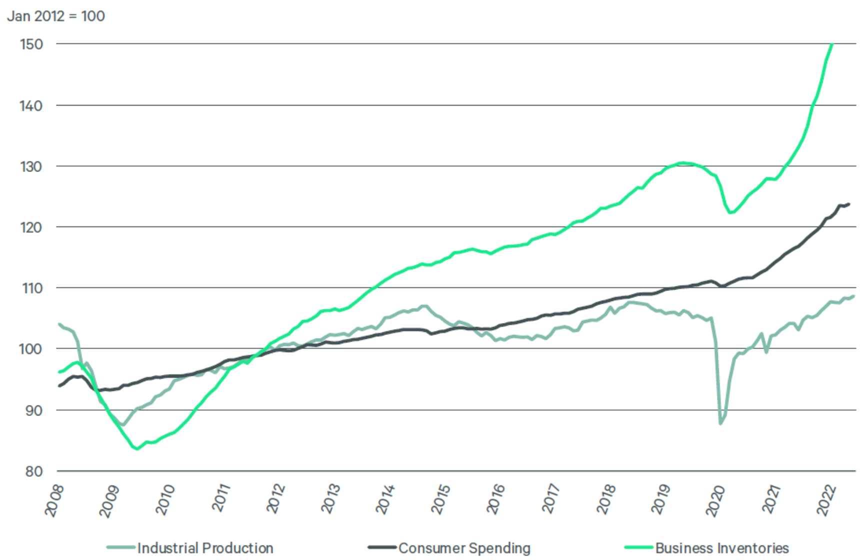

Figure 6 - Industrial Production, Consumer Spending, and Business Inventories (CBRE, 2022c)

All this of course has caused a rise in industrial rents never seen before in the market. Even with the decline of demand in 2022, rents have continued going up. This is shown in the graph below.

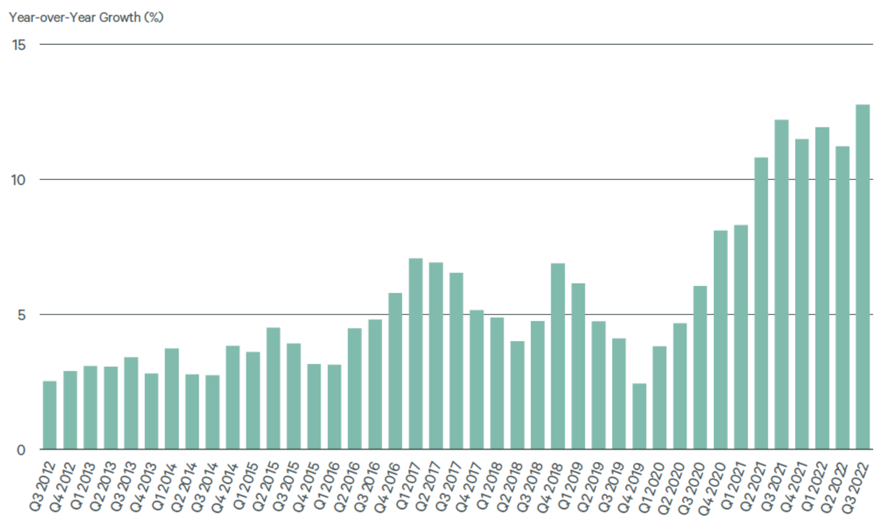

Figure 7 - Industrial Stock Year-over-Year Growth (CBRE, 2022c)

Finally, it is important to speak about the impact on investors' preferences. Starting with COVID-19, investments in real estate slowed in general. The residential market has seen very healthy growth in the past decade. The impacts of COVID on the demand for more and better space and the willingness to pay for it are still being studied and discussed. Other property types, like retail and office space, have lost the levels of equity they previously had.

Unlike the mentioned uses, industrial real estate was the only property type that increased the levels of equity invested through the pandemic and it has continued in that direction, as shown in the graph below.

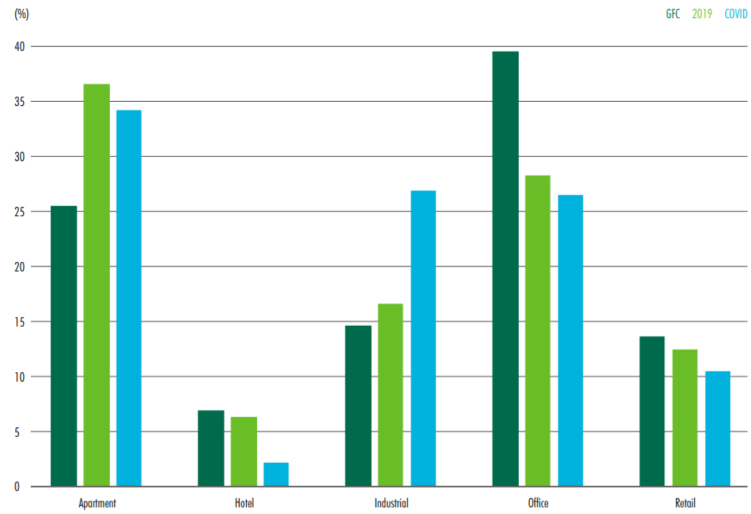

Figure 8 - "Investor Preferences Have Shifted" from Capital Markets U.S. Real Estate Market Outlook 2021 (CBRE, 2022a)

There has been a change in the way we live and buy things in the past few years. This shift has put the focus of real estate development on industrial buildings. Because of the rise in demand, rents, and investment, the construction of a new supply of industrial buildings has significantly increased. Industrial properties will probably continue occupying a higher percentage of the real estate stock than they did before COVID.

For this reason, this thesis will focus on construction systems for industrial buildings. Due to the need for sustainable initiatives to stop or slow down climate change, the relevance of the construction industry in that process, and the increase in the existing stock and new production of industrial real estate, the topic of this report will be reduced-carbon envelope systems for more sustainable industrial properties. After an overview of the topic, we will present definitions, the research methodology, and the thesis structure.

1.4. Definitions

Envelope System: The envelope system of a building consists of its exterior walls and roof. In an industrial building, these features account for the majority of the building above ground, as industrial buildings are typically one-floor structures with fewer interior divisions than other property types.

Green Premium: The extra cost of using more sustainable practices over traditional practices that emit more greenhouse gases. This term can also be understood as an extra market price.

Greenhouse Gas: There are many greenhouse gases. They differ in the amount of heat they can trap and how much time they will remain in the atmosphere. Carbon dioxide is the most common. Various gases are measured in carbon dioxide equivalents. This report will measure greenhouse gases, other than carbon dioxide, in their carbon dioxide equivalents. The terms for these gases, along with carbon dioxide, will be referred to as carbon, greenhouse gases, carbon dioxide, or CO_2.

Industrial Property: This type of property refers to buildings used for manufacturing industrial products, factories, power plants, warehouses, and freight and movement. Light industrial buildings are those that do not use capital-intensive machinery or production equipment; heavy industrial buildings do use such machinery or equipment.

Sustainable Initiatives: This term refers to initiatives such as projects, industry practices, and programs offering a reduced-carbon footprint or focused on reducing carbon emissions.

1.5. Research Methodology and Thesis Structure

This thesis will be focused on understanding the green premium of using reduced-carbon envelope systems for making more sustainable industrial properties. The final goal is to explore the cost of reducing the carbon footprint of industrial property construction. To do that, the next chapters will focus on evaluating real alternatives that are starting to be sold by material suppliers.

Chapter 2 will speak about how industrial buildings are being built now, highlighting traditional envelope systems, their greenhouse gas emissions, and their costs. The materials discussed will include Butler buildings, cast-in-place tilt-up concrete panels, and precast concrete panels.

Chapter 3 will focus on cross-laminated timber (CLT). This material, often referred to as mass timber, offers amazing possibilities for building reduced-carbon real estate. The first CLT large-scale industrial property in the United States was finished in Texas in 2022. This report will compare its embodied carbon to that of more traditional construction systems and the differences in their costs.

Chapter 4 will describe how people are starting to rethink concrete. It will speak about several technologies used to decarbonize concrete and how much they cost. The discussion will include the topic of developing reduced-carbon concrete panels for building industrial properties.

After explaining features of reduced-carbon systems, they will be compared through a case study. Chapter 5 will show what it would mean to use these systems for Arsenal Building 3, the third phase of an industrial park being built by Trammell Crow Company (TCC) in New Jersey. The report will include the green premium of the more sustainable systems and how much the reduction of embodied carbon could be. A unit price will be calculated for every kilogram of CO_2 not released into the atmosphere.

In presenting this study, the report will get to the question, “Do these alternative construction materials reduce CO_2 in industrial building construction, and by how much?” This will result in some development considerations for the private sector and suggestions for the role of policymakers in this process.

This thesis is a project done with the collaboration of the private sector, and its final goal is to give more clarity to developers facing the decision of what construction system they should use. An often-given reason why more sustainable initiatives are not adopted is the misinformation on decision-making. This thesis will, in the end, be a tool for developers to use to understand how much it would cost to reduce the carbon footprint of their buildings.

2. Traditional Envelope Construction

Unlike homes or workplaces, industrial constructions are properties that most people will never go to. These constructions might not come to mind as easily as houses or office buildings. To understand industrial construction systems, it is important to first be familiar with the characteristics of the types of structures needed to accommodate manufacturing and storage facilities.

The size of industrial buildings has drastically changed over time and is now more than double what it used to be in 1950 (Pham, 2021). Common warehouses were under 10,000 square feet (SF); they now exceed 25,000 SF. In fact, only 35% of warehouses are smaller than 25,000 SF. More than 50% of current, existing industrial buildings exceed 50,000 SF. Industrial buildings are considered large when they exceed 100,000 SF (Turner, 2020).

With the increase in e-commerce and the crisis of the supply chain, it is not uncommon to find industrial parks over one million SF with only a few tenants, and in some cases perhaps only one. To offer a comparison, the average home in the United States measures 2,480 SF (NeoMam Studios, 2022). An industrial park can be equivalent to more than four hundred average American homes.

A one-floor industrial building is essentially composed of a foundation, a base, a structure, a roof, and walls. Sometimes, the structure is embedded in the walls, as they carry the weight of the building. It is common for warehouses to have only one floor. The envelope of an industrial building consists of its walls and roof.

Industrial buildings should have a free height of at least 25 feet, and class-A structures are expected to have more than 40 feet. The walls needed to build class-A warehouses should be at least 45 feet tall.

As mentioned in the introduction, this report will focus on the envelope systems of industrial buildings. In this chapter, we will explain the traditional systems of industrial buildings.

2.1. Metal (Butler) Buildings

Metal industrial buildings are steel frame structures covered with walls and a roof that is also made out of steel. They are cheaper than other traditional envelope systems and easy to install, but they have height limits and problems regulating noise and temperature. A metal industrial building can only have free heights of 10 feet to 30 feet. If not recovered, steel is a sound transmitter and has a low barrier for heat transfer.

Butler Buildings is the most well-known brand for this type of structure and gives the system its colloquial name. It was founded in 1901 as a preassembled rust and leak-free tank manufacturer. It made its first all-steel framework building in 1909 (Metal Buildings, 2022). Below is an axonometric diagram of one of Butler's structural systems.

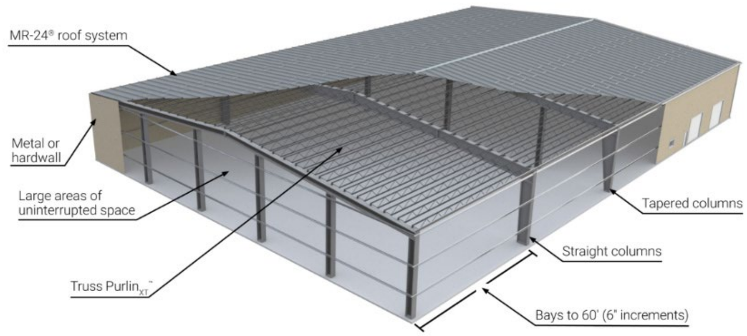

Figure 9 - Diagram Butler Landmark 200 (Butler Buildings Catalog)

Steel is both strong and easy to shape. To create the material, pure iron is combined with a small amount of carbon. Iron is not very strong on its own, but when carbon atoms nestle in-between iron atoms, it becomes a very resistant construction material.

Although both iron and carbon are easy to find, they need to go through a greenhouse gas-emitting process to create steel. Iron is normally found in the earth's crust almost always combined with oxygen. In this condition, it is named "iron ore." Iron ore needs to be separated from oxygen to become pure iron and it then needs to be combined with carbon.

Both processes can be done by melting iron ore with coal. At the necessary temperature, iron ore releases its oxygen and coal releases its carbon. A small amount of the carbon bonds with the iron, producing steel. The rest of the carbon bonds with the oxygen creating carbon dioxide. To create one ton of steel, 1.8 tons of CO_2 are released into the environment.

Steel is cheap to produce. Iron ore is very easy to get and therefore inexpensive. Coal is easy to find as well. If we continue using steel the way we are right now, by 2050 the world is expected to be producing 2.8 billion tons of steel every year, along with five billion tons of CO_2 (Gates, 2021).

2.2. Cast-in-Place Tilt-Up Panels

The second traditional envelope system discussed in this report consists of cast-in-place tilt-up concrete panels. Concrete elements have many advantages compared with Butler panels. They are more durable, isolate noise, and prevent heat transfer. These elements are made of reinforced concrete, an added insulating material, and a finishing layer.

Cast-in-place tilt-up panels get their name from the process involved in building and installing them. The panels are cast at the construction site and then lifted, or tilted up, into place.

To construct a cast-in-place tilt-up panel building, first, the casting surface is prepared. The panels are usually cast on the building's floor slab. The wood form is created leaving spaces for openings. After that, the structural reinforcing steel bars are put in place and the concrete is poured. Once cured, the structural wall is lifted and placed into its position. The insulation material, which is normally some type of foam, is then added to the interior face of the wall. Finally, a finishing material is placed over the insulation.

These panels can be even higher than 45 feet. They create better inner conditions than Butler panels. Nevertheless, having to cast and wait until the panels are cured at the construction site can delay planning schedules. The panels present the risk of not being able to control climate conditions on-site.

Below is a photo of a construction site showing how panels are being tilted up.

Figure 10 - Tilt-Up Construction (Tilt-wall Ontario Inc., 2022)

Reinforced concrete is a material that reflects engineering progress and has allowed development over the last two centuries. Nevertheless, it is one of the largest greenhouse gas emitters. Besides using steel rebar, its main material, as its name implies, is concrete.

Concrete is very commonly used, and it will probably continue being used in this manner in the future. “Today, second only to water, concrete is the most consumed material, with three tons per year used for every person in the world. Twice as much concrete is used in construction as all other building materials combined” (Gagg, 2014, p.1).

The production of concrete is extremely harmful to the environment. Concrete is made up of gravel, sand, water, and cement. To produce cement, limestone is burned to release calcium, one of its main components. Limestone also contains carbon and oxygen, and when exposed to high temperatures, the two remaining elements bond and produce carbon dioxide.

For every ton of cement made, a ton of CO_2 is released into the environment. If nothing changes, it is expected that by 2050 four billion tons of cement will be produced in the world annually (Gates, 2021).

2.3. Precast Concrete Panels

Precast concrete panels have the same materials as cast-in-place tilt-up concrete panels. However, unlike tilt-up walls, these elements have the insulating core material inside the structural wall. A precast concrete panel is a sandwich of insulation materials between two layers of reinforced concrete.

Additionally, the other main difference is that precast panels are produced in a manufacturing facility and not on the construction site.

Being produced in a factory has multiple benefits. First, the panels are cast in a controlled environment. This allows the concrete to have better and quicker curing. Besides that, it also allows a faster construction process, as the panels can be produced when the foundation and the slab are being built.

A precast panel system allows more precision and a more effective process. It reduces external risks while providing the conditions to limit mistakes to a minimum. Below is a photo of the installation of precast panels.

Figure 11 - Pre-Cast Panels Installation (Precast Concrete Wall Panels, n.d.)

The issue with this panel system, compared to the cast-in-place tilt-up panel construction system, is that it requires transportation for the panels from the factory to the site. This adds an extra cost to the construction budget. Moreover, it limits the size of the panels for them to fit in the vehicles.

Precast panels can also have a 45-foot height. They are normally no wider than 12 feet. Below is a photo of how these panels are transported to the construction site.

Figure 12 - Pre-Cast Panel Transportation (Mackley Carriers, n.d.)

Similar to the cast-in-place tilt-up concrete panels, precast panels are made of materials that are harmful to the environment: steel and concrete. Additionally, the transportation of precast panels increases their embodied carbon.

2.4. Measuring Embodied Carbon

It would not be realistic to calculate the precise amount of embodied carbon per area of facade for each construction system. The embodied carbon of a building depends on the location of the project, raw materials, the manufacturing facility, the type of energy used, transportation, and whether the building will be demolished or disassembled and reused, among other factors. Additionally, the end-of-life embodied carbon will probably change as cleaner energy and better sequestering technologies are developed.

"You would have to do an analysis for every piece and every application for every function. You'd have to know how long that piece was going to be in the structure. You'd have to know what the end of life was going to be. Is it going to be demolished? Is it going to be reused?" (E. Lorenz, 2022; as cited in Yee, 2022).

Since it is not possible to give a closed number of CO_2/SF for either traditional construction systems or more sustainable ones, we will use the assumptions of the case study for Arsenal Building 3. Through analysis of this case study, we will compare the costs and emissions of the traditional envelope system as well as the more sustainable ones.

The following chapters will describe the two alternative envelope systems for industrial buildings available in the American construction market. These systems are cross-laminated timber and reduced-carbon concrete panels. The next two chapters will include a discussion of the advantages and disadvantages of these materials and the assumptions of reduction in embodied carbon.

3. Cross-Laminated Timber

The popularity of mass timber is increasing among architects, builders, and developers. This is happening primarily because the material can substantially reduce greenhouse gas emissions in the real estate industry. Additionally, if planned correctly, there can also be a reduction in the costs associated with construction. Mass timber offers a profitable option for a net-zero future.

Structural timber is a new way of using wood to create more resistant elements. It is commonly known as "mass timber," short for "massive timber." The elements are created by sticking pieces of softwood together. The most used woods are coniferous species, like pine, spruce, or fir; less commonly, deciduous species are also used, like birch, ash, and beech (Roberts, 2020).

Elements of different sizes and functions are created by stacking and gluing layers of wood. Within the category of mass timber, there are several varieties, including laminated veneer lumber (LVL); nail-laminated timber (NLT); dowel-laminated timber (DLT); glue-laminated "glulam" beams; and the most common, cross-laminated timber (CLT).

CLT is made of layers of trimmed and kiln-dried lumber boards, stacked crosswise. They can be up to a foot thick and have a maximum size of 18 feet by 98 feet. The limitation on the size, similar to precast panels, depends on the type of transportation and not on the manufacturing process. The image below shows the detail of the corners of two CLT boards, revealing the crosswise stacked layers.

Figure 13 - Corner of CLT element (Franco, 2021)

The tallest building made of CLT and glulam beams was finished in Milwaukee, Wisconsin, in 2020. The 25-story and 284-foot-high tower surpassed Norway's Mjösa 18-story project (US Forest Service, 2022). An 80-story wooden skyscraper was proposed for Chicago (Sisson, 2017). Mass timber presents amazing opportunities that indicate the material could replace concrete and steel in the future.

This chapter will aim to show how CLT can be used for industrial buildings. Before getting into industrial construction, the report will offer an overview of the history of the creation and adoption of the material as well as discuss the advantages and disadvantages of CLT. After that, there will be an explanation of why CLT is less harmful to the environment than traditional construction techniques. Lastly, this will all be wrapped up to explain how CLT has been used in this report's property type.

3.1. History

Gerhard Schickhofer, a professor at the Graz University of Technology in Austria, created the first elements of CLT in the early 1990s. He was awarded the 2019 Marcus Wallenberg Prize for his efforts to standardize and popularize the material (EOS—European Organization of the Sawmill Industry, n.d.). During the 2000s, CLT was spread throughout all of Europe as a material for residential construction. Wood stick-frame construction, a system widely in use in the United States, has never been very common in Europe. CLT came in as a replacement for concrete and brick with the purpose of making residential real estate more sustainable.

In the United States, CLT was not able to compete with stick-frame construction, which is a cheaper, more standardized, and more accessible system. However, in the 2010s, it began being considered as a substitute for steel and concrete in larger structures. In 2015, CLT was incorporated into the International Building Code (IBC). Then, in 2021, changes were applied to the IBC to allow taller buildings made with mass timber structures.

CLT is becoming more popular in Europe and Canada. In the United States, restrictive building codes and limited domestic supply have stopped it from being more prevalent. The lack of incentives, plus regulations from local governments and misinformation on the possibilities of the material, have also slowed down the adoption of the construction system.

3.2. Qualities

The first attribute of CLT is that it works well in fire conditions because of the insulation of its inner layers. Unlike stick-frame and plywood elements, CLT is not flammable. Compressed fibers of wood are difficult to burn. In a fire, the outer layer will char and shield the interior of the element. A structure made of mass timber will retain its strength and original shape for several hours in a fire (Souza, 2022a).

Below is an image showing the section of an ignited piece of CLT. The outer layer was burned and became the protective char layer, while the inside of the element remained fine.

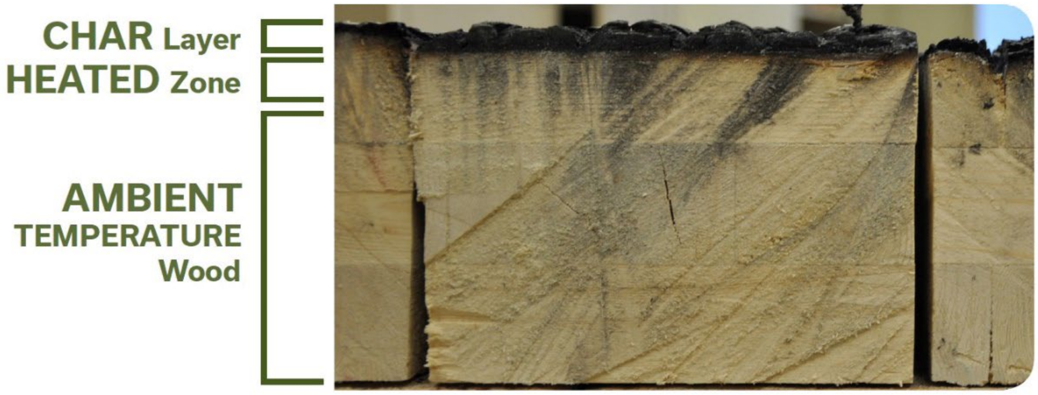

Figure 14 - Burned CLT (Souza, 2022a)

Different tests have been done to determine if CLT meets building codes. In one of them, a seven-inch-thick CLT wall lasted three hours and six minutes before igniting, exceeding the requirements by more than one hour (Think Wood, 2022a). Reports from the U.S. Forest Service, the International Code Council, and the Fire Protection Research Foundation have established that CLT meets the code for fire safety (Roberts, 2020).

CLT performs better than steel in fires. Steel buckles; CLT, on the other hand, burns in a slower time frame. Metals are highly unpredictable in yielding temperatures. This is of course extremely relevant for industrial buildings. Manufacturing facilities often have flammable processes. Warehouses made from CLT are safe in the event of a fire.

The second attribute of the CLT material is that it uses a more efficient construction process. Even now when mass timber elements have not reached the same scale in production as precast panels, building with them can reduce construction times, labor costs, and waste. According to Think Wood, the communications website founded by the Softwood Lumber Board, "Mass timber buildings are roughly 25% faster to construct than concrete buildings and require 90% less construction traffic" (Think Wood, 2022b).

A big part of the fabrication of CLT panels is done by computer numerical control (CNC) machines. This allows precision cuts. Using only plans, walls can be made to exact specifications.

The waste is reduced as no wood needs to be put in place for doorways or windows. Steel panels are shaped from a flat surface and their openings are then cut out. Concrete panels have openings unfilled from the beginning, but unlike CLT panels they need forms for casting, which also increases the amount of material waste.

Another advantage is that CLT elements can be fabricated quickly without having to go through the extra time required for curation. They can be sent to the construction site as needed, which avoids having large inventories and on-site space disruption. Lastly, as CLT elements are lighter, they require less machinery and people to work on assembling the pieces.

The Brock Commons Tallwood House project at the University of British Columbia is an 18-story hybrid mass-timber tower in which wood construction took two months and four days. The two cores, the foundation, the slab, and the first floor were built using reinforced concrete. The rest of the structure and the envelope were made in glulam beams and CLT panels. Below is an axonometric diagram of the building that shows the hybrid structure.

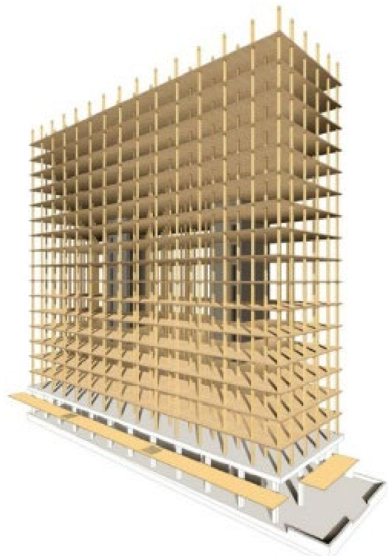

Figure 15 - Axonometric diagram of the structure of Brock Commons Tallwood House (Acton Ostry Architects Inc., 2022)

The construction only required nine trained wood installers on-site. There were 78 glulam columns per floor and 1,302 in the entire building. Each column took five to ten minutes to be installed. There were 29 CLT panels per floor and 464 in the entire building. Each CLT panel needed six to twelve minutes to be installed. The facade had in total 374 additional CLT panels, and each floor took eight hours to be installed. The nine workers built two floors per week. The whole construction was erected in less than ten weeks (UBC Sustainability, 2017). Below is a photo of the finished building.

Figure 16 - Exterior view Brock Commons Tallwood House (Acton Ostry Architects Inc., 2022)

The last quality of CLT, before getting into the environmental considerations, is that it performs well in earthquakes. Mass timber has been tested repeatedly and its performance in earthquakes has been outstanding. When an element breaks, it can easily be fixed, unlike a concrete panel that has to be replaced. Mass timber is flexible and lightweight, which makes it the perfect material to withstand an earthquake (Elser, 2017).

3.3. Problems

One of the two main problems of CLT, which will be addressed in the next section of this chapter, is that the material releases its embodied carbon at the end of its life cycle. The second problem is that the increase in demand for CLT will not be sustainable without climate-smart forestry.

Replacing native forests with the ones needed for CLT will contribute to climate change. The transformation or extinction of ecosystem services and wild animal habitats can have unprecedented impacts on nature's balance.

Besides that, and what might be worse, is that clearcutting the Earth's boreal forests releases an enormous amount of CO_2. North American forests might not even be sufficient to produce the CLT elements required by an increase in demand (NRDC, 2019). Forestry practices need to change in order for mass timber to be sustainable, which represents a major problem.

3.4. CLT's Embodied Carbon

As mentioned in the section above, CLT releases CO_2 in its supply chain and at the end of its life cycle. The techniques used for forestry, the type of vehicles that transport the wood, and the machinery used to cut it determine the amount of embodied carbon in the material. Although there are more sustainable managed forests now and there are more regulations for reforestation, it is not accurate to assume that all forestry is sustainable.

While the CO_2 released at the end of the life cycle of CLT panels might seem like a problem, as mentioned in the last section, it is not. This amount of carbon is not more than the amount released at the end of the tree's life if it would not have been cut. The fact that wood can trap greenhouse gas and delay the process of releasing it is actually positive. This is called "sequestering CO_2."

About this last point, the amount of CO_2 that CLT can sequester depends on the tree species. On average, one cubic meter of CLT traps 1.1 tons of greenhouse gas (Puettmann et al., 2019). If the element is not destroyed but reused, the carbon will remain sequestered. Wood can help us reduce our emissions by providing storage.

In the more sustainable processes of forestry and supply chains, the carbon emitted is less than the amount sequestered in CLT panels. In these cases, the material is carbon-negative. Hopefully, forestry processes and energy used for transportation, treatment, and manufacturing will become fully environmentally responsible. If that happens, building with CLT would not only stop contributing to climate change but would also help end it.

Nonetheless, knowing that this is not today's reality and that CLT production releases a known amount of CO_2, the main reason for using CLT right now is to avoid using steel and cement, which contain significantly larger amounts of embodied carbon. Concrete is responsible for 8% of global greenhouse gas emissions (Pearce, 2018). Iron and steel are responsible for 5% (IEA, 2016). These effects can be avoided by using mass timber.

There is not an exact reduction in CO_2 for every case of using CLT versus reinforced concrete. A study made in 2014 by the *Journal of Sustainable Forestry* said a building made of wood will have 14–31% less embodied carbon (Nassar et al., 2014). The *Journal of Building Engineering* said in 2019 that the average difference is 26.5% (Pierobon et al., 2019).

CLT's supply chain has a lot of room for improvement. Forestry, transportation, construction, and disposal practices need to be regulated to take this system to its full sustainable potential. However, CLT presents a much more environmentally responsible substitute for concrete and steel.

3.5. CLT in Industrial Buildings

Industrial buildings are a reflection of the most common, cheapest, and fastest construction systems of their time. In industrial Britain, factories were made out of red brick. In the United States currently, the use of steel and concrete seeks the appropriate ratio among efficiency, cost, and quality to follow the interests of the developer.

Although industrial projects appear to be simple buildings, the design of the materials and construction methods have gone through complex processes to get to where they are. The elements used in industrial buildings are planned and assembled to create open plans, flexibility in the layout, and high ceilings. That apparent simplicity is the goal of industrial properties, but behind it is an elaborate process of design and engineering.

The development of construction engineering software and machinery like CNC systems opened the possibility of using mass timber for industrial buildings. This made wood elements easy to manufacture and quick to assemble, allowing fast and continuous construction that is independent of seasons. In places like western Canada, wood is the economical choice for industrial buildings (Souza, 2021b). Below are some examples of industrial projects made in mass timber.

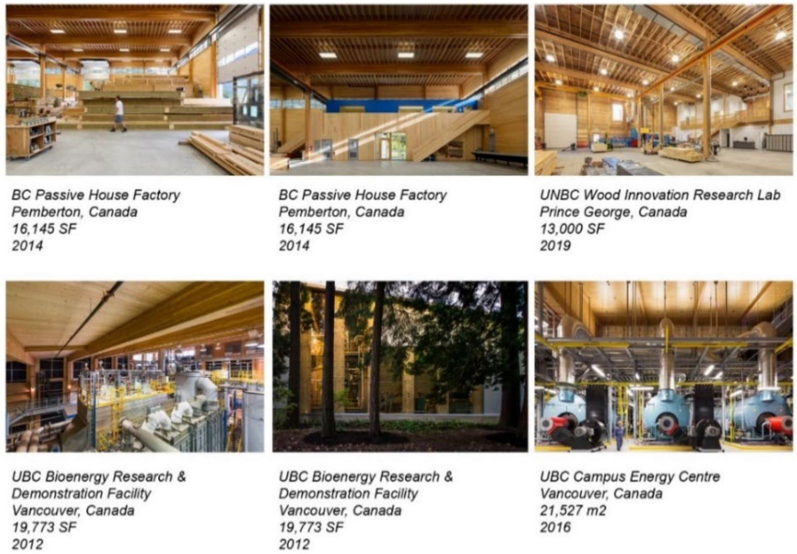

Figure 17 - Mass timber industrial buildings (Souza, 2021b)

This year, USAA Real Estate and Seefried Industrial Properties completed a 161,000 SF industrial building in Dallas, Texas. This building is located in the 157-acre Southfield Park 35. The design and construction team included Kalensikoff, Timberlab, Clayco, PDMS Design Group, and Hunter & Joiner Inc (Kalinoski, 2022).

The construction used 60-foot-long CLT panels stacked horizontally and was able to reduce its embodied carbon by 45%, according to documentation by USAA. To achieve those results, the wood was obtained through sustainable forestry. This is a successful example of the possibilities of the material made out of reforested wood, although it is not clear if the 45% reduction is only in the embodied carbon of the panels or the whole building.

Besides having excellent records of reduction of embodied carbon in the panels, USAA's warehouse exceeded previous sizes of mass timber industrial buildings. It was also one of the first industrial projects in CLT made in the United States. However, because CLT has little insulating value, a layer of insulation was installed on the exterior of the building, which then required a light-gauge metal envelope to protect it from the weather. It is not clear if the metal skin layer will be durable enough long-term in an industrial environment.

USAA did not reveal the exact cost increase. They said CLT had a slight premium to concrete (Kalinoski, 2022). Based on data from commercial construction, it is estimated that the increase is on average 26% of front-end costs (Gu et al., 2020). Below is an image of USAA's warehouse.

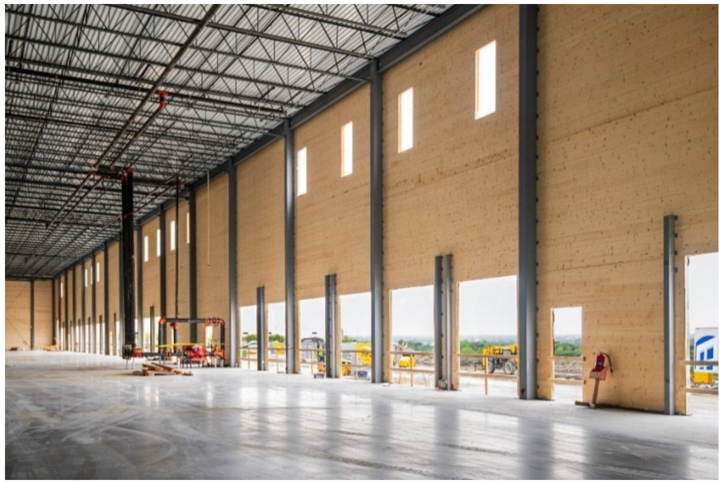

Figure 18 - Interior view - USAA CLT Warehouse (Frank, 2023)

3.6. Observations

The increasing demand for industrial construction requires us to work more diligently to utilize sustainable building systems. Because institutional industrial buildings are made primarily of concrete and steel, and because more environmentally friendly options for these two construction materials are a number of years away due to the required scaling of green hydrogen as a fuel source, CLT is a great option that, besides being better for the environment, can be more efficient and cheaper if produced on a larger scale.

USAA's project will hopefully lead the way for developers using mass timber for the property type. Nevertheless, the use of this system should increase with sustainable forestry. The further loss of local species and mature forests could undo the benefits of carbon reduction. There should be regulations demanding certificates like the ones given by the Sustainable Forestry Initiative and the Forest Stewardship Council.

In the next chapter, we will speak about decarbonized concrete as another alternative to traditional construction systems. After that, we will make a price/CO_2 comparison of CLT, decarbonized concrete panels, and the systems explained in chapter 2.

4. Rethinking Concrete

As mentioned in previous chapters, 8% of global carbon emissions come from concrete. In addition, 80% of that CO_2 is released in cement production, and from that amount, 60% comes from the calcination of calcium carbonates, the process described in chapter 2 (Khung, 2022). To stop this trend, besides the proposals based on naturally grown materials, there have been different initiatives to create low-carbon concrete.

This chapter will start with an overview of different strategies to reduce carbon emissions in concrete production. It will then address the costs and benefits of the proposals. After that, the discussion will turn to their implementation in industrial construction. Finally, the low-carbon concrete product used in the case study's comparative analysis will be introduced.

4.1. Different Strategies Used to Create Carbon-Reduced Concrete

The first strategy is to cut emissions in the production of cement. Sixty percent of the carbon released in the calcination process, which comes from the reaction of the elements mentioned above, cannot be addressed through electrification and clean energy. To tackle these emissions, there have been some proposals to use alternative materials to create cement.

By adding some unbaked limestone, the carbon emissions can be reduced by up to 10%. Limestone is not as resistant on its own, but it can be used to help Portland cement harden when mixed with water. This technique is already being used in Europe and is becoming more popular in the United States.

Another option is to use mineral-rich industrial waste instead of cement. Blast-furnace slag from steel mills will harden when it is mixed with water. The slag will act like standard cement due to its high calcium content. Fly ash from coal-fired power plants can also harden when it is mixed with cement and water. There may be a large amount of CO_2 released to produce these wastes, but using them in cement will not release additional amounts. Two centuries of industrialization have left an extensive accumulation of these materials. Although it is not a long-term solution, because producing more waste will release more greenhouse gas, it can be implemented now and can cut emissions from 27% to 43%.

Manganese is also being used as a replacement for limestone. In this proposal, the byproduct, built by Brimstone, absorbs more CO_2 than it releases in the chemical reaction and the heating process. This is a carbon-negative option in development.

Finally, the most promising alternative to cement is geopolymers; these are inorganic polymers composed of aluminum, silicon, and oxygen (Kriven, 2021). When mixed with alkaline solutions, they can be stronger and more resistant to water, fire, and weathering than Portland cement. They can be made using elements found in slag, fly ash, and even clay. There is no shortage of raw materials, and creating them is another way of getting rid of waste products. Using geopolymers can cut emissions by up to 80%.

In the first strategy—cutting emissions from the production of cement—40% of CO_2 released in a calcination reaction comes from the heat needed. This process requires a temperature hotter than lava, which is currently created by burning coal or natural gas. One option to change this is to make all-electric processes powered by renewables. Another idea being developed is using hydrogen instead of fossil fuels.

While these proposals are only projects in progress, if they ever become feasible, 40% of the CO_2 released in the calcination reaction would not be a problem anymore.

The second strategy is to maximize concrete efficiency. By reducing the amount of concrete needed, less cement will be used and less CO_2 will be released. One of the ways in which this can be done is by putting concrete only where it is strictly needed. The concrete 3D printers proposed by researchers at the Graz University of Technology in Austria are one of the proposals to achieve that. With their machines, it is possible to create void-filled elements that place concrete only where it is essential (Graz University of Technology, 2022).

The other solution to achieve this is to increase the concrete's strength. An approach developed by researchers at the University of Exeter is to use water and cement mixed with graphene. This makes concrete 146% stronger. Their research indicates that the cement used can be cut in half (Dimov et al., 2018). This proposal still needs to lower its production costs to be a possible solution for the built environment.

The third solution is to enable the carbonation reaction. After the concrete is cured, the carbonation reaction is a natural process in which cement-making is reversed. When calcium hydroxide in concrete is exposed to carbon dioxide in the air, they try to form calcium carbonate. According to a study published in *Nature Geoscience*, old concrete structures have already absorbed 43% of the CO_2 released in their production (Xi et al., 2016).

A number of companies are trying to develop technologies to enhance that process. Some of these proposals are based on injecting CO_2 into wet concrete. Builders regularly try to avoid carbonation, as steel rebar can corrode in the process. However, if injected into fresh concrete, the steel is surrounded by a protective oxide layer due to the alkaline environment. This is Carbon Cure's proposal, which is being utilized throughout the United States sporadically via franchise agreements but has not been fully tested by the American Concrete Institute for long-term effects.

Other companies have tried to achieve this result by exposing the calcium-rich waste product to the gas coming out of the initial calcination reaction, thus trapping the CO_2 and creating calcium carbonate again. One of these companies—Blue Planet Systems—says this is a net-zero solution (Blue Planet Systems, 2021).

All the proposals described above are only starting to be used. For this reason, they increase construction costs without necessarily reducing emissions in a significant way. In the next section, we will study the costs and benefits of these proposals to rethink concrete.

4.2. Costs and Benefits of the Systems

Currently, the strategy of limiting the use of cement might be the most effective one. In her research project "Life Cycle Assessment (LCA) and Cost-Benefit Analysis for Low Carbon Concrete and Cement Mix Designs," made for the Sustainable Development Solutions Network, Delaney Khung shows that there are options in the market that can reduce CO_2 emissions up to 43%. The product that can reduce greenhouse gases up to that number is the previously mentioned ground granulated blast furnace slag

(GGBS). Using fly ash can reduce gases by 27%. The production of the solutions in the market can cost up to 21% more, while GGBS or fly ash only costs 7% more (Khung, 2022).

Unfortunately, the other proposals mentioned in the previous section are only in development or are not yet feasible to be considered carbon-reduced products in the market. Below are the explanations and current situations of the various options.

Solutions dependent on renewables or other cleaner ways to create heat are still in development. Several products can be made with green energies, but the impact on carbon emissions and price depends on many other factors. However, electricity accounts for 27% of global emissions. Although there is not a clear cost-benefit number, it is extremely important to start using energies that will lower emissions.

Maximizing concrete efficiency raises the costs, making its use unfeasible. To achieve the solutions mentioned above, 3D printers need to be made on a larger production scale to be affordable. Likewise, using graphene in concrete makes it unfeasible. This proposal needs to lower production costs in order to be a salable market product.

Finally, the startups working to enable carbonation reactions are only beginning their operations. The ones that are pursuing CO_2 injection have only been able to reduce emissions by 10%. This technology aims to reduce emissions by 33% in order to improve its processes. On the other hand, trapping CO_2 with waste presents a net-zero proposal. If this is standardized and implemented, it could be a low-cost option.

Currently, the only option to make net-zero concrete is using fossil fuels and trapping CO_2 with carbon-capture devices. This method increases concrete costs from 75% to 140% (Gates, 2021).

Even if all this might indicate that low-carbon concrete is not yet feasible, technologies are improving at a fast pace. Therefore, it is important to learn about the processes mentioned above and understand that this report is based on the information available today. These proposals and many others will present improvements in the topic.

For now, construction companies need to stay informed about the options in the market. It is necessary to increase demand before supply becomes cheaper. Companies need to focus on products that can actually reduce carbon emissions and weigh these considerations and their willingness to pay in their feasibility analysis.

4.3. Low-Carbon Concrete in Industrial Building Construction

Several companies are working on prefabricated low-carbon concrete panels. The various approaches include the strategies explained in section one of this chapter. Some companies are using different mixes; others focus on cleaner energy, more efficient concrete, and carbon capture. The importance of stopping climate change is reflected in the prefabricated products available in the market.

Unfortunately, panels designed for other uses do not work for warehouse construction. Industrial buildings require panel dimensions different from the ones used in other property types. This, combined with the very low relevance given to constructing more sustainable industrial structures, makes it hard to find low-carbon panels for this use in the market.

An increase in demand for low-carbon class-A industrial panels would have a positive impact on the available supply, making them a more reasonable option for development companies. Currently, developers need to analyze if it is feasible paying the increase in costs to achieve reductions in the embodied carbon of their buildings. This is what Trammell Crow Company is doing for the case study we will analyze in the report. The last section of this chapter will be about the low-carbon precast product TCC is considering using for the Arsenal 3 Building.

4.4. Low-Carbon Concrete Precast Panels (LCCPP) Analyzed

In the analysis presented in the next chapter, the numbers for low-carbon concrete will be from a proposal made to TCC for Arsenal Building 3. Due to the lack of 45-foot-tall carbon-reduced panels in the market, the development company has worked with suppliers asking them to contemplate developing class-A industrial walls. From these efforts, they received the price and the embodied carbon estimate used in this report.

As mentioned before, there are many different technologies in development to lower the embodied carbon of concrete. It is important to mention that this analysis will use one possible option in the market and that its numbers do not reflect other systems. This section will have an explanation of the product in the analysis and its approach to reducing concrete's carbon footprint.

The panel in consideration is made from an insulating core supported by a steel frame and covered in two exterior layers of a proprietary formula. Its performance characteristics are similar to concrete. The formula is 99% free of International Living Future Institute (ILFI) red-list materials. It also has no volatile organic compounds and no fossil-derived materials. Additionally, it is stronger and lighter than concrete. In the panels, each exterior layer measures one-half to three-quarters of an inch. Their weight is one-fifth of a standard precast concrete panel.

This product has been used for commercial, residential, and small-scale industrial spaces. A third-party Life Cycle Assessment (LCA) said projects built with this system have on average 31% less embodied carbon than similar projects made with traditional prefabricated systems.

Before TCC considered using this material, the supply company had started constructing a small-scale industrial building. Their panels had a maximum size of 12 feet by 36 feet. Since TCC started working with them, they began considering production of larger panels to accommodate class-A industrial needs.

With the current design of the panels, TCC would need to construct an additional perimeter steel structure for Arsenal Building 3 to support the roof joists that would traditionally be supported by tilt-up or precast concrete panels. It would also need additional site preparation that traditional construction systems would not. This will not only increase costs but also increase carbon emissions.

All the mentioned considerations will be weighted in the next chapter, which will be the comparative analysis between tilt-up, precast, CLT, and LCCPP systems. The analysis will set a price for the reduction of CO_2 emissions for industrial building construction.

5. Comparison of the Discussed Systems in Arsenal Building 3: A Case Study

As mentioned before, giving a general price for a kilogram of CO_2 not released into the environment for a construction system would not be accurate. The embodied carbon of each material depends on many different variables that are unique to every project they are used for. Due to that reason, rather than offer a general value for each system, this report will focus on the case study of Arsenal Building 3.

Nevertheless, more than just making a recommendation on which construction system is the best for this specific project, using a case study will try to give a snapshot of how viable it is to build with more sustainable systems at this moment. The numbers of Arsenal Building 3 will not be the exact numbers for other cases, but they will show overall assessments of the construction systems in consideration.

Having this case study in our report will allow us to understand how much more expensive it may be to build more sustainable industrial buildings. The first section of the chapter offers an introduction to the project. After that, the assumptions and considerations used will be laid out. Later, the prior results including production, transportation, and erection will be shown. Following this, site preparation, installation, and disposition will be considered as well to complete the analysis. Finally, the report will give a price per kilogram of CO_2 not released into the environment for the construction systems in Arsenal Building 3 as compared to a baseline.

5.1. Introduction to the Building

Trammell Crow Company is constructing Arsenal, a speculative three-building industrial park in the borough of Sayreville, Middlesex County, New Jersey. Construction of the project began in April 2022. The project is located less than an hour from Manhattan, which makes it ideal for accessing the metropolitan area and providing for easy delivery of goods.

TCC is currently constructing all three buildings simultaneously in the industrial park. The third building will be the case study of the report. It will be a 451,602 SF, one-floor structure.

Arsenal Building 3 is a 375-foot-wide, single-bay, open-plan warehouse. Its overall building length is 1,210 feet. It has loading docks and trailer parking spaces on one of the long sides and automobile parking on the shorter sides. The building is located on the north side of the industrial park. This project is being built as a speculative industrial development planned to house the operations of one to four tenants. Below is Arsenal's plan.

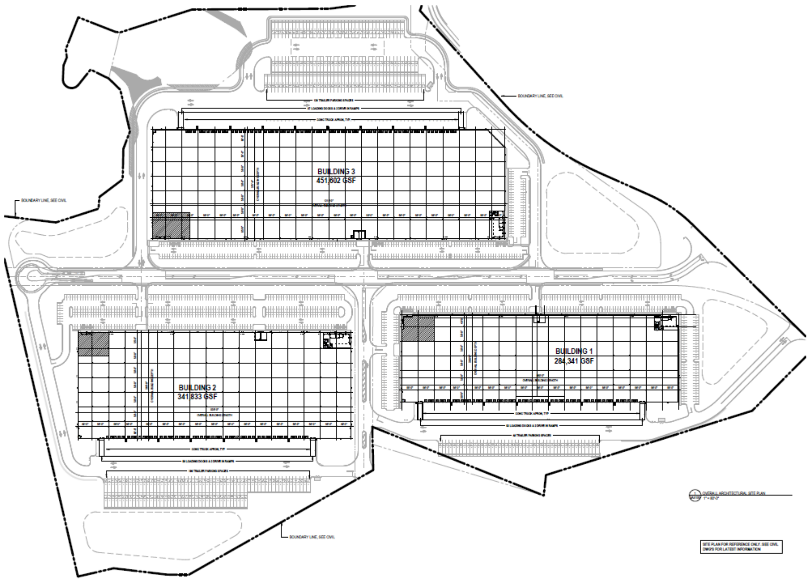

Figure 19 - Arsenal Industrial Park Site Plan (Trammell Crow Company)

TCC is interested in using more sustainable construction materials for all of its buildings and is using this project as a means of investigating which products might be best suited for that effort. Understanding this requires that they work closely with suppliers to make it possible.

5.2. Assumptions and Considerations

This study will analyze the costs and benefits of using LCCPP, CLT, and precast panels. All options will be compared to cast-in-place tilt-up panels, as they are considered to be less expensive and are the current market standard.

Following that, the cost premium and embodied carbon reduction will be measured as the percentage difference to tilt-up values (formulas 1 and 2). The price per kilogram of CO_2 not released into the environment will be measured as the difference in the cost of the system to tilt up panels over the difference in embodied carbon (formula 3).

$$Percentage\ cost\ premium = \frac{(Cost\ system\ X - Cost\ tilt\ up)}{Cost\ tilt\ up}$$

$$Percentage\ emissions\ reduction = \frac{(Emissions\ system\ X - Emisisons\ tilt\ up)}{Emissions\ tilt\ up}$$

$$Cost\ /\ kgCO_2e = \frac{(Cost\ system\ X - Cost\ tilt\ up)}{(Emissions\ tilt\ up - Emissions\ system\ X)}$$

To better understand the life-cycle stages of construction systems, the total cost and embodied carbon will be divided into production and transportation, erection, site preparation and installation, and disposition. Production and transportation are studied together as the costs for tilt-up and precast panels usually include both, and thus to offer a comparison of numbers evenly with low-carbon concrete and CLT systems.

Production and transportation of tilt-up panels mean the extraction and transportation of raw materials and the panels production on-site. For precast, CLT, and LCCPP, it means extraction and transportation of raw materials to the factory, fabrication of the pieces, and transportation to the construction site. In the production stage, insulation is added only to precast and LCCPP. For the other two, the production only accounts for their core material. The erection is placing the pieces in their final position on the building.

Site preparation and installation vary among the construction systems. For CLT and LCCPP, it includes building a knee wall and a steel frame structure, which will be explained in the following paragraphs. CLT and tilt-up also require the installation of insulation. Additionally, CLT requires exterior cladding to protect the insulation layer. The only processes shared between all construction systems are caulking and interior painting.

The end-of-life stage is demolishing or disassembling the buildings and removing the waste from the site. CLT and LCCPP are assumed to be disassembled and reused. Tilt-up and precast panels are assumed to be demolished.

The timing was not considered in the study due to how its impact on construction costs is so different among projects. In order to have an analysis that more accurately reflect the situation of the general market, only financial costs will be considered.

The first analysis is about emissions and costs in the early life-cycle stages. We looked at production, transportation, and erection.

The costs used in this analysis came from proposals made by suppliers for the low-carbon concrete and precast systems. For the other two, we used comparable projects with an adjustment for the change in the size of the buildings. In the case of tilt-up and CLT, the comparable projects were in Texas. For them, we used the same production and transportation costs and increased the erection cost by 25% to account for the union premiums.

The embodied carbon of these stages was taken from a third-party LCA provided by suppliers for the LCCPP and tilt-up panels options. Precast production and erection embodied carbon was assumed to be equal to tilt-up panels plus the insulation emissions.

CLT emissions were calculated using the difference in embodied carbon from its main material and reinforced concrete. CLT's embodied carbon under the current raw-material extraction and transportation technologies is 219 kg/m^3, and reinforced concrete's is 635 kg/m^3. The difference between the materials for embodied carbon is 66% (Pliteq Inc., 2022). CLT's production number was 34% of tilt-up embodied carbon. Its erection was assumed to be the average between CLT and tilt-up.

Subsequently, the end-of-life emissions were taken into consideration. Tilt-up and precast panels were assumed to be demolished and CLT and LCCPP were to be disassembled and reused. The industry standard for demolishing that kind of product in that location is $5/SF. Literature on the topic suggests that the cost of disassembling is on average 17% more (Dantana et al., 2005; Diyamandoglu & Fortuna, 2015; Küpfer et al., 2013; O'Brien et al., 2006), so for CLT and carbon-reduced concrete the cost of disposition was $5.85/SF.

The LCA included the end-of-life emissions for LCCPP and tilt-up panels. CLT and LCCPP disposition emissions were assumed to be equal, and precast and tilt-up numbers were too.

Finally, after working with the suppliers and studying how more sustainable options could be installed, TCC realized that to install the LCCPP and CLT, they needed additional site preparation and installation. First, it was necessary to build a reinforced concrete stem wall to prevent the LCCPP and CLT systems from coming into contact with the ground directly during the backfilling process; additionally, they needed an extra steel structure. Finally, CLT needed extra insulation and exterior cladding.

Because the CLT and LCCPP are not sufficiently strong to carry the vertical perimeter loads of the roof structure, a perimeter structural steel system is required (as seen in the photo of the USAA CLT warehouse in chapter 3) for both of these systems to support not only the panels themselves but also the roof loads. This structural steel frame introduces significant additional costs and carbon emissions to these two systems.

TCC requested the general contractor and the steel subcontractor provide the total price (purchase, transportation, and erection) and tonnage for a steel system to support the LCCPP system. The steel structure for CLT is smaller and the price for it was taken from the comparable project. In both cases, the system needs to support the roof loads primarily, which is the predominant set of forces, with the lateral loads to support the walls being smaller in general.

Finally, for CLT, additional exterior cladding and insulation were needed. Because CLT has very little insulative value, a layer of three-inch polystyrene sheeting was installed on the entire perimeter of the building, with a waterproof sheathing on top of that, before a corrugated metal skin was finally applied.

Site preparation and installation were considered another life-cycle stage in the study. Below are two drawings made by TCC showing site preparation and installations needed to use LCCPP or CLT. The dock wall footing section shows the stem or knee wall and the steel frame section shows the additional metal structure.

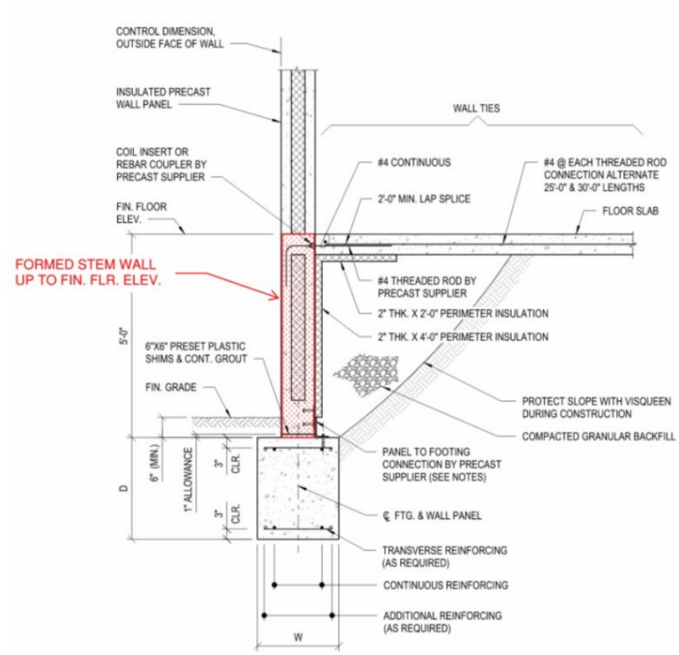

Figure 20 - Dock Wall Footing Section (Trammell Crow Company)

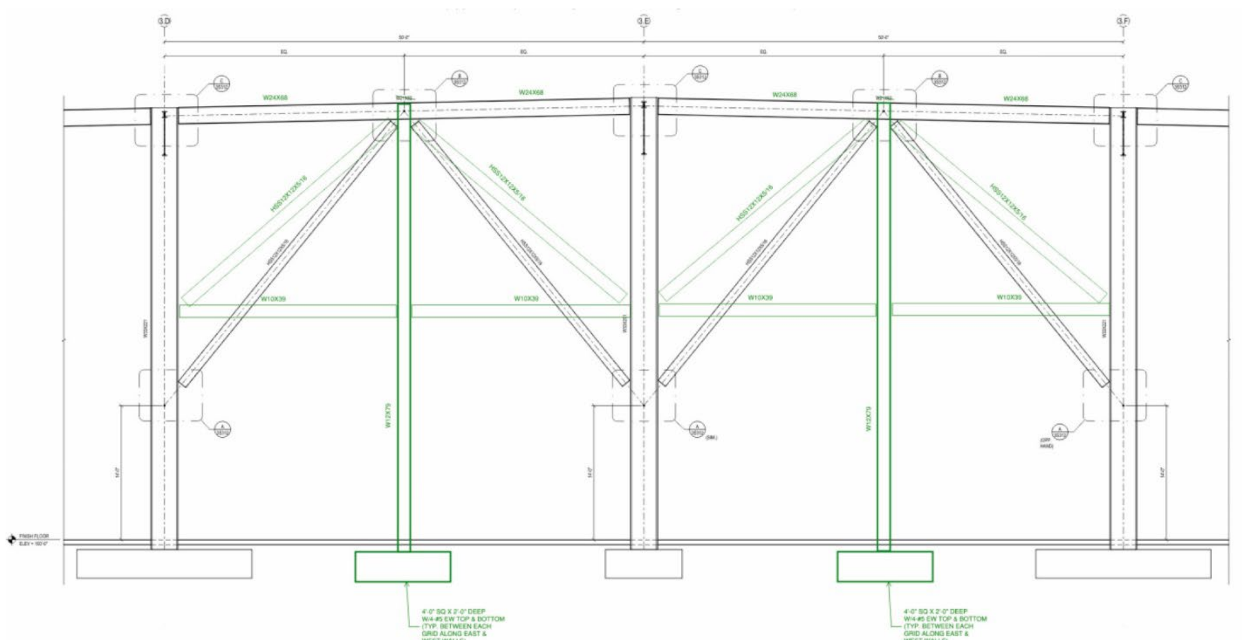

Figure 21 - Raised Chevron Brace Concept Section (Trammell Crow Company)

The costs of the site prep were taken from the comparable projects in Texas for CLT and tilt-up panels. The numbers were adjusted for union premiums and the difference in the size of the building. Proposals from contractors were used for LCCPP and precast.

The embodied carbon was calculated in precast panels using the percentage difference in costs between the site prep and the production. As both life-stage processes are based on reinforced concrete, the emissions were assumed to have the same ratio as the costs. Site prep costs are ~8% of the production costs. Site prep emissions were assumed to be ~8% of production emissions. Tilt-up was assumed to have the same site prep emissions plus insulation. CLT site prep emissions were calculated with the percentage difference in costs to tilt-up. LCCPP was assumed to have the same emissions as CLT minus the insulation.

5.3. Early Results

As mentioned above, the first study was only about the early life-cycle stages of the construction systems. In production and transportation, the LCCPP analyzed is significantly more expensive than the other systems, followed by precast, with 104% and 50% differences to tilt-up panels respectively. In the erection, precast has the larger difference. The table and graph below show the difference between carbon-reduced concrete panels and precast costs to CLT and tilt-up panels.

Table 1 - Early Life Stage Costs

Costs						
	Production and Transportation		Erection		Total	
	$	%	$	%	$	%
LCCPP	$4,211,164	104%	$636,882	31%	$4,848,046	90%
CLT	$2,132,017	3%	$781,740	61%	$2,913,757	14%
Pre-cast	$3,095,095	50%	$826,905	70%	$3,922,000	54%
Tilt-up	$2,063,793	0%	$486,242	0%	$2,550,035	0%

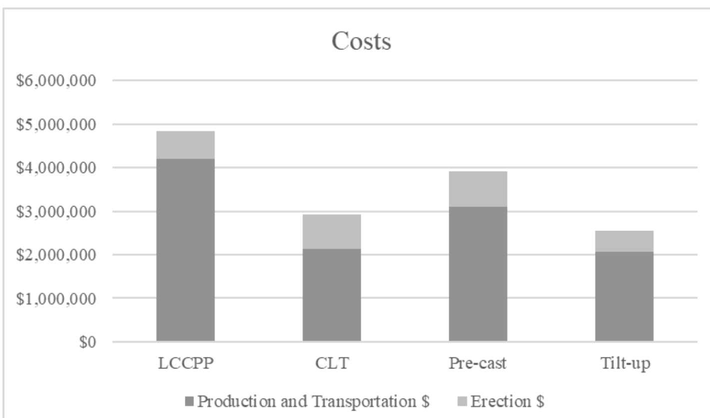

Figure 22 - Early Life Cycle Stages Costs

In the early stages, precast panels have higher embodied carbon than tilt-up, as they have insulation core emissions included in their production. This is also the case for LCCPP, although its emissions are lower. For tilt-up and CLT, the insulation carbon is included in the site prep, as it is added after the panels are erected. CLT is the only material that has a significant difference from tilt-up, with 62% of the early stages of embodied carbon.

Table 2 - Early Life Stages Emissions

Carbon Emissions						
	Production		Erection		Total	
	Kg CO2e	%	Kg CO2e	%	Kg CO2e	%
LCCPP	161,372	-5%	7,606	-61%	168,978	-11%
CLT	58,608	-66%	13,467	-30%	72,075	-62%
Pre-cast	193,552	14%	19,328	0%	212,880	12%
Tilt-up	169,937	0%	19,328	0%	189,265	0%

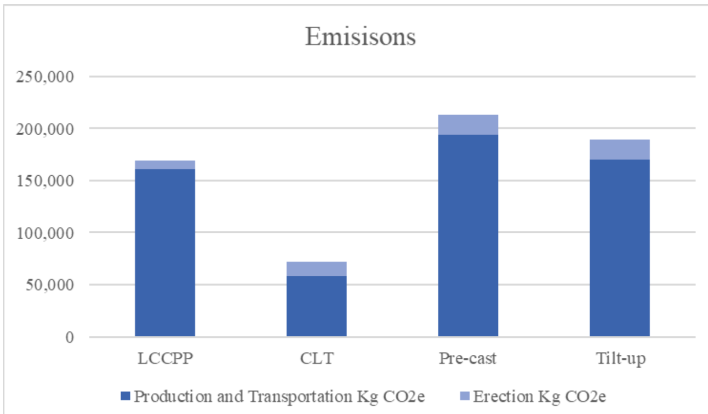

Figure 23 - Early Life Stages Emissions

5.4. Complete Comparative Analysis

The disposition of the construction systems is a stage that increases the difference in carbon emissions for more sustainable buildings. As mentioned above, the study is assuming CLT and the carbon-reduced concrete buildings will be disassembled and reused. Precast and tilt-up panels will be demolished. Disassembling a building is only 17% more expensive while reducing the embodied carbon by 68%. This consideration increased the difference in emissions between LCCPP and CLT panels to tilt-up panels to 14% and 62%, respectively. The results are shown in the tables below.

Table 3 - Costs Including Disposition

Costs								
	Production and Transportation		Erection		Disposition		Total	
	$	%	$	%	$	%	$	%
LCCPP	$4,211,164	104%	$636,882	31%	$2,641,872	17%	$7,489,917	56%
CLT	$2,132,017	3%	$781,740	61%	$2,641,872	17%	$5,555,629	16%
Pre-cast	$3,095,095	50%	$826,905	70%	$2,258,010	0%	$6,180,010	29%
Tilt-up	$2,063,793	0%	$486,242	0%	$2,258,010	0%	$4,808,045	0%

Table 4 - Emissions Including Disposition

Carbon Emissions								
	Production		Erection		End of life		Total	
	Kg CO2e	%	Kg CO2e	%	Kg CO2e	%	Kg CO2e	%
LCCPP	161,372	-5%	7,606	-61%	3,670	-68%	172,648	-14%
CLT	58,608	-66%	13,467	-30%	3,670	-68%	75,745	-62%
Pre-cast	193,552	14%	19,328	0%	11,614	0%	224,494	12%
Tilt-up	169,937	0%	19,328	0%	11,614	0%	200,879	0%

Nevertheless, as explained in the last section, the more sustainable systems require adding a knee wall and an additional steel frame structure to install the panels. CLT also needs exterior cladding. All site preparation and installations are assumed to be done in traditional construction systems. Extra knee walls and steel frame structures make the sustainable-focused proposals significantly more expensive and harmful to climate change.

Below are the final results of the study that show that CLT is 69% more expensive than tilt-up, LCCPP is 66%, and precast is 16%. The price difference in the last life-cycle stage considered was 416% for CLT. This is because of the exterior metal cladding. According to the comparable project, the cladding is 95% of the original panel price.

Table 5 - Complete Analysis Costs

Costs										
	Production and Transportation		Erection		Site Prep & Installation		Disposition		Total	
	$	%	$	%	$	%	$	%	$	%
LCCPP	$4,211,164	104%	$636,882	31%	$1,736,720	134%	$2,641,872	17%	$9,226,637	66%
CLT	$2,132,017	3%	$781,740	61%	$3,830,524	416%	$2,641,872	17%	$9,386,153	69%
Pre-cast	$3,095,095	50%	$826,905	70%	$256,411	-65%	$2,258,010	0%	$6,436,421	16%
Tilt-up	$2,063,793	0%	$486,242	0%	$742,653	0%	$2,258,010	0%	$5,550,697	0%

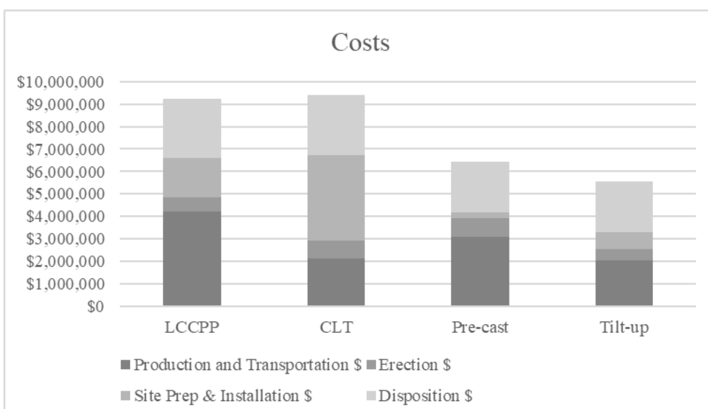

Figure 24 – Complete Analysis Costs

The final results also show that including the consideration of the site preparation and installation considerably changes the total carbon emissions. Using LCCPP would increase the embodied carbon of the envelope by 47%, CLT would also increase it by 17%, and precast has the same CO_2 emissions. This is shown in the exhibits below.

Table 6 - Complete Analysis Emissions

Carbon Emissions										
	Production		Erection		Site Prep & Installation		End of life		Total	
	Kg CO2e	%	Kg CO2e	%	Kg CO2e	%	Kg CO2e	%	Kg CO2e	%
LCCPP	161,372	-5%	7,606	-61%	180,894	356%	3,670	-68%	353,542	47%
CLT	58,608	-66%	13,467	-30%	204,509	416%	3,670	-68%	280,254	17%
Pre-cast	193,552	14%	19,328	0%	16,035	-60%	11,614	0%	240,529	0%
Tilt-up	169,937	0%	19,328	0%	39,650	0%	11,614	0%	240,529	0%

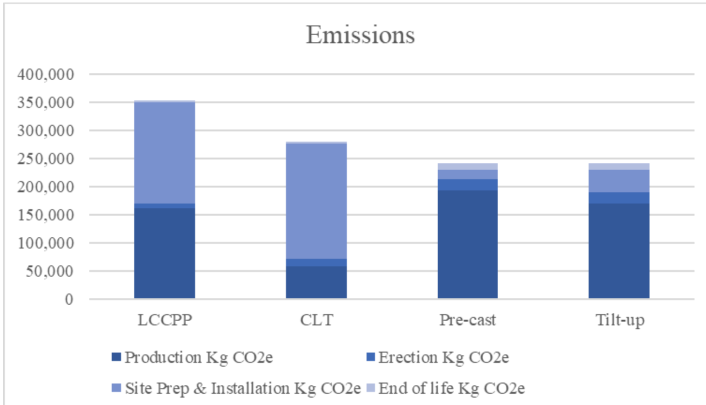

Figure 25 – Complete Analysis Emissions

5.5. Price per Kg CO_2

The results above show that the studied LCCPP and CLT are still products in development. Using them in Arsenal Building 3 would increase costs by 66% to 69% and emissions by 17% to 47%.

The table below shows prices for releasing more CO_2 instead of reducing it. The CLT price is higher, because it has an overall higher price and because it releases less carbon than LCCPP. These numbers are saying that it is easier, or cheaper, to release more CO_2 using LCCPP. This is, of course, not desirable. Precast, being a system 16% more expensive than tilt-up, has the same embodied carbon. This information is shown in the table and graph below.

Table 7 - Price per $KgCO_2e$

Price per kg Co2e					
	$/Kg CO2e production	$/Kg CO2e erection	$/Kg CO2e site prep & installation	$/Kg CO2e disposition	**$/Kg CO2e total**
LCCPP	$250.71	$12.85	-$7.04	$48.32	**-$32.53**
CLT	$0.61	$50.42	-$18.73	$48.32	**-$96.55**
Pre-cast	-$43.67	No change in carbon	-$20.59	No change in carbon	**No change in carbon**

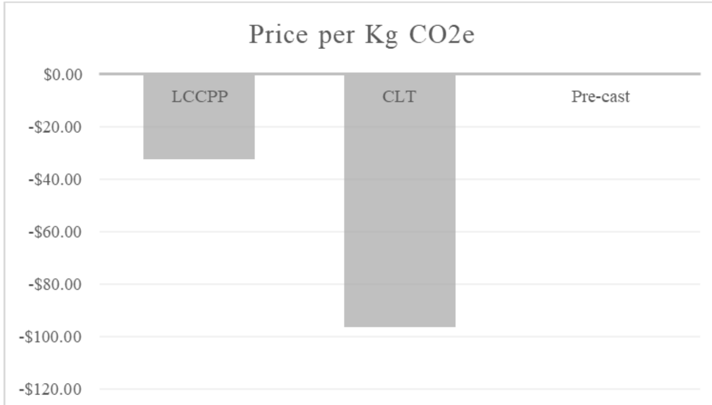

Figure 26 - Price per KgCO$_2$e

The emissions of the two more sustainable construction systems are lower in all the life-cycle stages except site prep and installation. The overall results of the analysis are transformed by the extra site preparation and installation requirements. While working to reduce embodied carbon in material production, the other processes of construction should not be ignored. Positive change is only possible if all the parts of building development are taken into account.

Industrial construction pieces have been rigorously designed to improve the efficiency of building processes on-site. To compete with them, all the considerations used in their design should be included. Sustainable proposals need to be self-supporting, water- and earth-resistant, and insulated to replace more traditional elements. Currently, building industrial properties with LCCPP and CLT is more expensive and worse for the environment.

6. Conclusions

6.1. How Close Are the Current Alternative Construction Systems to Net Zero?

The results of the previous chapter indicate current technologies are still works in progress. Reducing the embodied carbon of one component of construction affects other processes. Solutions need to account for the impacts that they have on other parts of the construction process.

What would seem to be the conclusion to the last chapter is that using more sustainable technologies today carries a significant increase in construction costs and thus is not worth it. Nevertheless, for the reasons explained throughout the other chapters, it is necessary to reduce the embodied carbon of industrial buildings. Consequently, the main conclusion of this report is that a lot of effort needs to be put into making the explained systems feasible and making the construction industry sustainable.

For sustainable technologies to become the industry's best practices, they first need to be developed, adopted, and standardized. Both LCCPP and CLT are in development for being used in industrial building construction.

Three big problems for both technologies to get to standardization are the lack of information, the unwillingness to pay, and the absence of readiness to adopt. New technologies will always represent a liability for construction budgets and schedules. Without overcoming the three challenges, the construction industry will never get to net zero.

The last chapter of the report focuses on considerations for the private and public sectors to realize the adoption and standardization of more sustainable construction systems. The next two sections will be roadmaps for making industrial properties sustainable and will be followed by closing thoughts.

6.2. Development Considerations

Efforts to implement sustainable initiatives to stop a company from being competitive in the market will end up having more problems than benefits. Doing so and not being able to get financing and investors, or even not being able to make a project profitable, will take out of the competition a company that was trying to make an effort to stop climate change. To see real transformations, the industry needs those companies. Accordingly, corporations must try to use the most sustainable construction systems that will allow them to be competitive in the market.

As mentioned before, misinformation and an unwillingness to pay for and adopt new techniques can stop companies from lowering the embodied carbon of their buildings. Corporations always need to be informed about the latest developments in construction technologies. They need to assess how possible it is to implement sustainable initiatives while remaining in the market. And they need to figure out how to reduce the liability of implementing new systems without ruling them out.

A way to fight misinformation, untenable prices, and risks is to work closely with supply companies. Partnering with suppliers in the research, design, and development of new products can help standardize practices and ensure material meets the needs of the construction budget and schedule. To help improve processes and results, developers can gain knowledge about new possibilities, and suppliers can focus on knowing exactly what developers need in order to improve processes and results. In order to make industrial construction more sustainable, developers need to stay informed, analyze different options to see if any are feasible, and mitigate risks in adopting these options.

6.3. Policy Considerations

The examples of how governmental regulations have had impacts on industry standards are numerous. Speaking of emissions, the U.S. Clean Air Act is a good example. Since its amendment in 1990, it has reduced poisonous emissions of nitrogen dioxide by 56%, carbon monoxide by 77%, and sulfur dioxide by 88% (Gates, 2021).

To make the construction industry more sustainable, different strategies should be implemented in policymaking. One of the strategies is helping the adoption of sustainable initiatives become a more competitive process. By complying with regulations like setting a price on carbon emissions, or using incentives like tax exemptions, governments can help sustainable construction systems become truly competitive with traditional ones. This strategy is referred to by Bill Gates as “leveling the playing field” (Gates, 2021, p. 257).

Governments should also invest in the development and standardization of sustainable proposals. In the same way they financed the COVID vaccine and made it available for entire countries, policymakers should end the investment gap resulting from the lack of private funding for public interests. Climate change may not be an immediate threat but it needs to be addressed now.

Finally, governments need to work with the private sector along with fostering partnerships between developers and suppliers. If different groups of actors interested in fighting climate change join their efforts, expertise, and objectives, the solutions will come faster and will be more adequate and implementable to achieve large-scale results.

6.4. Final Thoughts

Climate change is a problem that is often easy to ignore. Although the results of climate change are disrupting life in communities that are under environmental threats, it is not a process that currently affects everyone evenly or constantly. The people who are more vulnerable are also the ones with less power to stop it.

Luckily, developers, investors, construction companies, suppliers, and consultants are becoming more aware of the problems that climate change will present and the urgency to stop emitting more CO_2. The efforts of the different players should be aligned to work toward a more sustainable future.

The report mentions several key areas for making the construction of industrial buildings more sustainable, including research and education, combined efforts, mitigation of risks, leveling the playing field, and public funding. If both public and private groups of actors tackle each of these areas in the interest of developing and adopting more sustainable construction systems, emissions in this part of the industry can be significantly reduced.

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