Cob Versus Conventional Building Materials: A Life Cycle Assessment Case Study of a Cob Bench in Northwestern Pennsylvania



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ABSTRACT

This study involves the construction and analysis of a cob bench in Northwestern Pennsylvania against theoretical benches made from conventional materials. Cob is touted as an environmentally sustainable building style as its main building components are clay, sand, straw, and water. This study details the creation of a bench made of cob as well as its analysis. The analysis is conducted with the creation of a Life Cycle Assessment (LCA) of the cob bench versus an LCA of an aluminum bench and an LCA of a hardwood bench. Conventional construction is one of the greatest contributors to environmental damage and greenhouse gas emissions worldwide. As Earth's population continues to grow, new materials and building styles are necessary to mitigate the environmental impacts of construction. By studying the benefits and limitations of building with cob, new ideas are brought to the subject of sustainable construction.

ACKNOLWEDGEMENTS

I would like to take this time to help the long list of people who made this study possible. First, I would like to thank my family, namely my mom and dad for getting me through the largest building hurdles of this project. Without them, I don't know how I would have finished. They saved me so much time and so many tears.

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With the utmost sincerity,
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Introduction:

Construction has many environmental consequences, one of the most detrimental being greenhouse gas emissions (GHGs). The transportation, manufacture of building materials, and final demolition of structures produces one-third of the world's emissions and creates a vast amount of waste (European Commission, 2016; United Nations Environment Programme, 2009; Yan et al., 2010). In the United States, construction accounts for 39% of total greenhouse gas emissions, which is higher than both industrial and transportation sectors (Environmental and Energy Study Institute, 2005). As a result of Earth's population continuing to increase and countries becoming more developed, more buildings will need to be constructed. Focusing on the materials, equipment, and design used in the construction of these new buildings can reduce many of the environmental consequences (Yan et al, 2010; Sandanayake et al., 2016; European Commission, 2016). An example of three high-impact construction materials which are commonly used include concrete, hardwoods, and aluminium.

Concrete is arguably the most common building material, as it is used in sidewalks, roads, houses, and office buildings (Crow, 2008). One of the reasons it is so common is because it is relatively inexpensive and is very durable (Crow, 2008). Unfortunately, concrete has a very high environmental impact in part because the materials involved go through kilns at temperatures of 1,480^{o}C (Babor, Plian, & Judele, 2009). Heating a kiln to this temperature requires a great amount of energy which primarily comes from coal (Babor, Plian, & Judele, 2009). Using fossil fuels produces a lot of different GHGs which exacerbate climate change. In addition, the many materials that go into concrete require high energy and transportation inputs. As Babor, Plian, & Judele (2009) say in their study, "Cement production is one of the most energy intensive of all industrial manufacturing processes. Including direct fuel use for mining and transporting raw materials, cement production takes about 1,758 kWh for every ton of cement". Cement is also made by using coal as a fuel source (Babor, Plian, & Judele, 2009). This leads to very high levels of CO_2 output as coal is the fossil fuel which produces the most CO_2 when used. For example, bituminous coal produces 205.7lbs

CO_2 per 1 British Thermal Unit (BTU) (U.S. Energy Information Administration, 2016). Each ton of bituminous coal is roughly 24 million BTUs, so therefore 1 ton of coal equals over 49 billion pounds of CO_2 (Alternate Heating Systems).

In Norgate, Jahanshahi, & Rankin's 2007 study on the environmental impact of metal production, aluminium was second in Global Warming Potential for metals (GWP), just under titanium. Its carbon footprint was 22.4kg CO_2e/kg, whereas the lowest value was lead at 2.1kg CO_2e/kg. As developing countries continue to increase building construction, their demand for aluminum will grow, and so will its impact on the Earth.

Finally, hardwood is another commonly used building material. Bergman & Bowe (2008) conducted a study on the environmental impact of producing hardwood. Drying and manufacturing lumber used a large amount of energy: 608MJ/m^3 went towards drying the hardwood, and and 5.8GJ/m^3 was for manufacturing (Bergman & Bowe, 2008). The fuels used to power these processes included natural gas, coal, and wood fuel. Using natural gas produced 14.4kg CO_2/m^3, wood fuel produced 26.6kg CO_2/m^3, and 35.3kg CO_2/m^3 was produced with coal. They found the total carbon input required for manufacturing hardwood was 915kg CO_2/m^3 for plane [sic] dried lumber. 670kg of carbon came from logs, 170kg from wood fuel, and 75kg from bark (Bergman & Bowe, 2008). For these reasons, it is imperative that we begin looking at other materials with which to build.

For these reasons, there has been a push for more environmentally-friendly construction practices and materials from consumers and governments (Barton, 2015). Sustainable or 'green' construction begins to address these issues by using sustainably produced materials that protect ecosystems and are less toxic to humans (Ghani, 2012). To do this, natural and synthetic products are manufactured and transported, such as recycled aluminum, glass, and concrete (Kim & Rigdon, 1998). Taking the central tenets of green construction--lessening environmental impact through design and materials, natural building styles such as cob go even further to reduce environmental impact. Instead of attempting to synthetically produce building materials

that are *less* harmful for the environment, nearly all of the materials used in cob construction are waste products and natural materials that are ideally sourced from near the building site. Examples of these materials include straw, clay, and sand. Straw is a natural waste product from the production of grains that is mainly used for bedding as it can't be used for food, whereas sand and clay exist in various combinations in nearly any soil. Mixing a specific ratio of these materials along with water creates a natural type of concrete called cob (Niroumand et al., 2013).

A typical cob mix is 10%-25% clay, 50%-80% coarse sand or aggregate, and roughly 10% straw (Evans, Smiley, & Smith, 2002; McClellan, 2013). Cob is made by hand, creating soft, round loaves which are placed on top of one another, compressed and molded into a solid form and left to harden before additional loaves are added (Chiras, 2002; Forster et al., 2008; Niroumand, Zain, & Jamil, 2013b; Bird, 2013; Snell & Callahan, 2005). After the cob has dried, it has turned into a solid, durable, aesthetically pleasing monolithic structure (Niroumand et al., 2013). Wood is used to help make a frame for the cob as well as when adding windows and other building features.

In comparison to conventional building, earth building with cob is much less energy intensive. For example, a study done by Houben in 2011 found it only takes 5-10 kWh to make a cubic meter of natural building material such as cob on site. In comparison, making the equivalent amount of concrete takes 400-800 kWh, and 1,140 kWh to produce the same amount of solid brick (Houben, 2011). One reason for this is because earth building construction attempts to use the resources available around a site such as clay, mud, sand, and local hardwoods (Chrias, 2002; Houben, 1997; Morel et al., 2001).

Because cob construction attempts to use the materials around a specific site, each cob structure is unique (Evans, Smith, & Smiley, 2002). For example, a cobber in Northwestern Pennsylvania might include local sugar maple wood in their project instead of importing Oregon bigleaf maple (Pennsylvania State University, 2016; Nash, 2016). In this way, natural building is more sustainable versus conventional construction because it drastically reduces the amount of greenhouse gas emissions from

transportation (Chrias, 2002; Houben, 1997; Morel et al., 2001; Ngowi, 1997; Rowland, 2011; Weismann & Bryce, 2007; Zami & Lee, 2001). In addition, it reduces material emissions because they are not heated and processed as common building materials would be (Chrias, 2002; Houben, 1997; Morel et al., 2001; Ngowi, 1997; Rowland, 2011; Weismann & Bryce, 2007; Zami & Lee, 2001).

Cob is a technique that has been used in the UK for centuries (Evans, Smiley, & Smith, 2002; McClellan, 2013; Weismann & Bryce, 2007). Houses were being built with cob since the 1200s, but became increasingly popular in the 1500s (Smith, 1999). Some of these houses are still around today, such as one house in Devon, UK that is over 600 years old (Smith, 1999).

Regardless of the regional variations, cob always has the main components of coarse sand and clay. Both Evans, Smiley, & Smith (2002) as well as Weismann & Bryce (2007) both agree that clay can be found nearly anywhere--it is just harder to find in certain regions of the world.





Figure 1. **Top:** An example of regional differences for cob. Taken from Evans, Smiley, & Smith, 2002, p. 110). **Bottom:** A real-world example of cob designs blending into the landscape. Taken from Weismann & Bryce, 2007).

Thus far, the author is aware of only one previous Life Cycle Analysis (LCA) of cob: a case study of a cob house in Nicaragua (Estrada, 2013). An LCA attempts to assess the environmental impact of a certain product within certain time and geographical boundaries. Estrada's 2013 LCA compares a 60 square meter cob house to a 60 square meter concrete block house. The scope of Estrada's (2013) LCA included the acquisition, processing, and transportation of both raw and purchased materials. She compared the CO_2 emissions of production and transportation between the cob and the concrete houses (Estrada, 2013). The results of this study concluded that cob produced less than half of the carbon that the concrete house produced. The cob house's carbon value was 8,340kg CO_2 whereas the concrete house emitted 18,525kg CO_2.

Because there is only one Life Cycle Assessment (LCA) of cob and it only references a residential building, it is important to conduct more LCAs to get a full scope if cob is a viable. Specifically, these LCAs should focus on whether cob is a more environmentally friendly option than conventional construction and if it works in multiple climates and applications. For these reasons, the goal of this study is focused on determining the viability and environmental impact of a cob bench in Northwestern Pennsylvania (NWPA) through creating the bench along with a cradle-to-site Life Cycle Assessment. An LCA was chosen because it is the only established way of getting numerical data for an environmental impact study. Cradle-to-site means that this particular analysis takes into account all of the environmental impacts of the raw materials (including extraction processes) up until the point the product is constructed on site (Circular Ecology Ltd., 2016).

In the summer of 2016, I created a bench out of cob. The bench was created as there were no cob structures in NWPA. It is located at the Meadville Area Recreation Center on 800 Thurston Road, Meadville, PA, 16335 USA. To test the claims that earth building is more environmentally friendly than conventional construction, I also created a

LCA of my cob bench. This was compared to LCAs of two other benches made of conventional materials which I did not build. The other benches were made from aluminium and hardwood, respectively. Both have similar dimensions to my bench.

Methods:

The methods section will give a detailed step-by-step view of how I created my cob bench as well as the how the LCA was conducted.

How to Make Cob - Overview

There are nine major steps to build any project out of cob. They include 1) siting and sourcing clay, 2) creating a shelter for the cob, 3) creating the design for the structure including a frame for which to hold the cob, 4) site preparation and materials stockpiling, 5) building a drainage system and stem wall foundation, 6) testing the cob mix, 7) making the cob itself, 8) making plaster or other protections, and 9) decorating the cob (Evans, Smiley, & Smith, 2002; Weismann & Bryce, 2007). I will be briefly detailing each of these processes and how I did them to make my bench.

Background Information and Precautions with Cob

Cob is a mixture of coarse sand, clay, and dry straw. The proportions of each respective material are roughly 50%-80% sand, 10%-25% clay, and 10% straw, but each batch of cob has a different ratio of materials. Most often an acceptable ratio of clay and sand can be sourced from subsoil around each building site, though it is very possible extra clay or sand will need to be added to create a better mix.

Because cob is unfired clay, it needs to be protected from water as much as possible (Evans, Smith, & Smiley, 2002; Weismann & Bryce, 2007). Cob that is fully dry is somewhat protected from water, as would be any dry unfired clay product. This being said, were it to be sitting in a wet area or be constantly in the presence of water, the cob would begin to absorb the water and lose its structural integrity (Evans, Smith, & Smiley, 2002; Weismann & Bryce, 2007). For this reason, a good cob structure needs a sturdy

"hat" and "boots" (Evans, Smith, & Smiley, 2002). The hat in this scenario is a roof, to protect the cob from rainfall and other precipitation (Evans, Smith, & Smiley, 2002). The boots comprise ground drainage and the 'stem wall' or stone foundation which lifts the cob above ground level (Evans, Smith, & Smiley, 2002). The function of the boots is to divert groundwater away from the foundation as well as lift the cob to where groundwater cannot reach (Evans, Smith, & Smiley, 2002). This helps prevent the foundation from sinking or shifting, which would crack the cob that rests above (Evans, Smith, & Smiley, 2002). It is best for cob to be as seamless as possible, so that any possible water that would rest on it would have a hard time penetrating its interior (Evans, Smith, & Smiley, 2002; Weismann & Bryce, 2007).

Siting and Testing for Clay

Perhaps the two most important aspects of a cob project is the site itself and finding a clay source (Evans, Smith, & Smiley, 2002; Weismann & Bryce, 2007). There are many factors to take into consideration, such as how wet the land is, how much sun it gets, and if it's in a valley or on the side of a hill. Each influences the general aesthetic of what the cob will look like in the landscape and its potential design, as well as possible construction benefits or drawbacks, as shown in *Figure 1* above (Evans, Smith, & Smiley, 2002; Weismann & Bryce, 2007). As stated above, it is important to divert all water away from the cob structure as much as possible. Because of this, making a cob house in a valley of a wet climate is strongly discouraged (Evans, Smith, & Smiley, 2002; Weismann & Bryce, 2007).

It is wise to do jar tests (discussed in *Figure 3* below) before deciding on a site. Jar tests allow a cobber to roughly determine the different levels of sand, silt, and clay in the surrounding soil. As cob is primarily made of sand and clay, sites that do not have good proportions of these are less favorable than those which do. That being said, sites which do not have very good proportions of sand and clay can still be used for cob, they will simply need to be supplemented by outside sources of these materials.

Typically I would have looked at multiple areas and conducted jar tests before choosing a site, but I was very limited in where I could build. Because I was not allowed to build this bench on Allegheny's campus, Kerstin Martin offered an area at the Meadville Area Recreation Complex on 800 Thurston Road, Meadville, PA 16335. The relatively flat site was located in the middle of a gravel garden path (see *Figure 2* below). The path opened to a half circle that bordered a small asphalt walkway. In all of the possible configurations of where my bench would be placed and where it would face, I chose the bottom left-hand section of the half-circle, as my bench would face the growing garden and the trees separating the MARC from the next-door senior high school.



Figure 2. **Top:** A picture depicting the building site of my cob bench at the Meadville Area Recreation Complex (MARC) facing towards the bridge to the Meadville Area Senior High School. **Bottom:** A picture of the building site looking facing towards the parking lot of the MARC as well as its skatepark.

After I chose this area within the garden, I began testing for clay. This is typically done by doing a jar or shake test: filling a quart mason jar roughly ⅔ with water, and then filling the jar roughly ⅓ of the way with subsoil in the jar and adding some salt to help separation (Evans, Smith, & Smiley, 2002, p.122; Weismann & Bryce, 2007). See *Figure 3* below.





Figure 3. **Top:** A graphic depicting what a possible jar test may look like, and how different subsoil layers will separate over time. Taken from A.M. Leonard's Gardener's Edge. (n.d.). [Soil Jar Test]. Retrieved from https://s-media-cache-ak0.pinimg.com/564x/23/1f/71/231f71e92988a81aff141e90313e6fb1.jpg **Bottom:** A picture of my jar test. Layers are not visible because the lighting did not allow for clear definition.

When the ingredients were added, I vigorously shook the jar for at least a minute, then set it down on a flat surface and watched it separate. Coarse sand precipitated first, within roughly 5 seconds (Evans, Smith, & Smiley, 2002). Fine sand and silt came

next, and then clay (Evans, Smith, & Smiley, 2002; Weismann & Bryce, 2007). All of the precipitated material equaled 100% of the total subsoil within the jar. The figure above suggests letting the jar rest overnight--this is acceptable to do, but most material separates enough to make general quantitative measurements within a few hours (Evans, Smith, & Smiley, 2002; Weismann & Bryce, 2007). Category estimations of each type of subsoil are made by determining how thick each individual layer is as a proportion of the total. The jar test serves to give the user an idea of the composition of the excavated subsoil. As stated previously, the best cob mixes are between 50%-80% coarse sand and 10%-25% clay, and the existing soil may need to be adjusted by adding either clay or sand to get a better proportion (Evans, Smith, & Smiley, 2002; Weismann & Bryce, 2007).

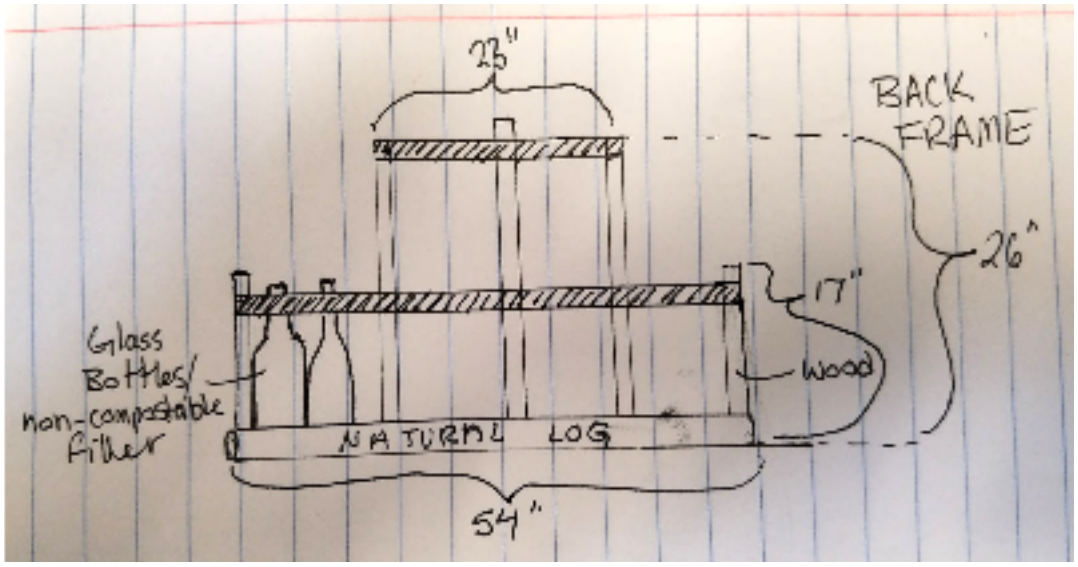
Unfortunately, the dirt around my site had high silt content and little to no clay. I tried many options to get clay--for example, calling all excavation contractors within the area and asking if they have 'compactable fill', which is said to be a workable cob mix and a waste product for them--but my efforts were not fruitful. For that reason, I had to ask Allegheny College's art department for 1 50lb bag of powdered Hawthorne fire clay and 1 50lb bag of Old Mine #4 (OM4) ball clay.

Making a "Hat"

Typically, all cob projects have overhead protection from precipitation. Because I was already building a bench itself, my academic advisors suggested not to build a roof, as it would be too much for one project. In terms of dimensions of any particular "hat", the only requirement is that it protects the cob from rain. In a routine cob project, the roof would be one of the first items built, as to shelter the cob and materials from the elements. The roof over my cob project has not been built at this time, but Kerstin and I had consulted a local builder about what the design might look like by the time of this writing.

Making a Design

The geometry of cob favors rounded designs versus those which are incorporate right angles, which are typically not found in nature (Evans, Smith, & Smiley, 2002). Keeping this in mind, I made a design with a rounded back whose highest point existed in the middle. I took bench dimensions from some outside benches on campus in order to determine average dimensions for my bench. My bench is 54” (4.5ft) long, the seat is 16.5” (1.375ft) wide and 13” (1.083ft) high, and the back ranges from 17” (1.416ft) high to 26” (2.16ft) high at its tallest point. The seat of the bench is made entirely out of natural stone, reclaimed concrete, and reclaimed patio tiles.



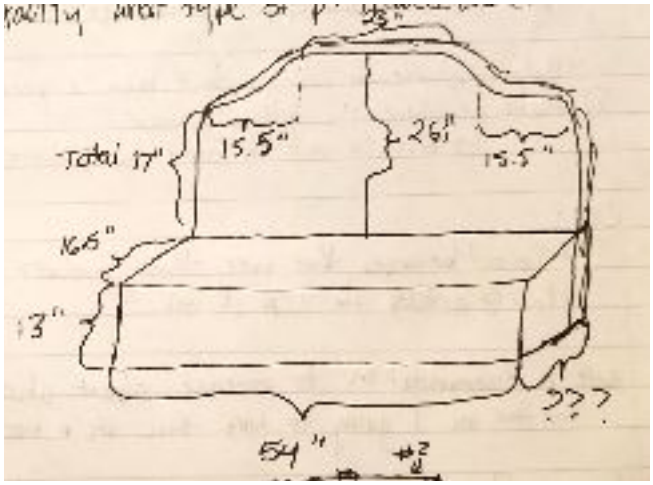


Figure 4. **Top:** drawings for the internal frame composing the back of the bench.

Bottom: dimensions and design for the entire bench.

Materials and Preparation

Common tools in cob construction include the following: shovels, plastic tarps, a mattock to break hard soil, 5 gallon buckets, gloves, eye protection, scissors, screws, trowels, and drills. Materials generally include straw, coarse sand, clay, stones for the stem wall foundation, and mortar of some sort (cement or lime).

To first prepare my site, it needed to be cleared of all organic matter and anything which obstructed the dirt. This meant I needed to clear away the pre-existing gravel on the garden path. I did so with a shovel, and piled it close to my worksite as I would use it later. To test how rainwater would flow on my site, I filled 3 five-gallon buckets and poured them at different points at the edges of where I was planning to build. I made note of the fact that water pooled at the bottom right of my planned bench area, shown in *Figure 5* below. After the dirt was uncovered, I dug light lines and placed orange flags in the edges to guide where I would later dig the drainage system.





Figure 5. Clearing the building site and marking lines for future digging. Red lines represent the future trench, white lines represent the future foundation and stem wall. The blue circle is where water originally pooled on the site.

How to Make "Boots"

The second most important part contributing to the longevity of a cob project is the "boots", or the drainage and stem wall. A stem wall is simply a stone foundation which lifts cob off the ground and protects it from rainwater. The drainage serves to take water away from underneath the stem wall foundation. The system I built involved digging a trench around where the stem wall would eventually rest, as well as connecting the trench to drainage under the stem wall itself. Because water pooled near the right side of my bench as shown in *Figure 5* above, I modified my trench design to also include a deeper hole away from the bench, along with grading the trench so that water would be more inclined to go towards the hole. These two steps made sure water would not pool around the bench area. Roughly three inches under the ground existed a black barrier to prevent weed growth. To get to the underlying dirt, I had to cut through this barrier. The ground underneath was very hard and I used a mattock to break up the earth before excavating it.



Figure 6. Digging the perimeter trench. The deepest point is the hole at the top middle of the photo where the water will run towards. The white outline in the middle of the photo is where the foundation drainage and stem wall will go.

The trench around the stem wall was 7ft long by 4.5ft wide. The trench width itself was 6 inches, and its depth ranged from 1.25ft to 1.5ft. I wanted to make it a slight decline towards a deeper hole that I dug to the side of the perimeter trench. Before digging the drainage under the stem wall, I backfilled the trench with gravel as to give support to the dirt in between the trench and the stem wall drainage.

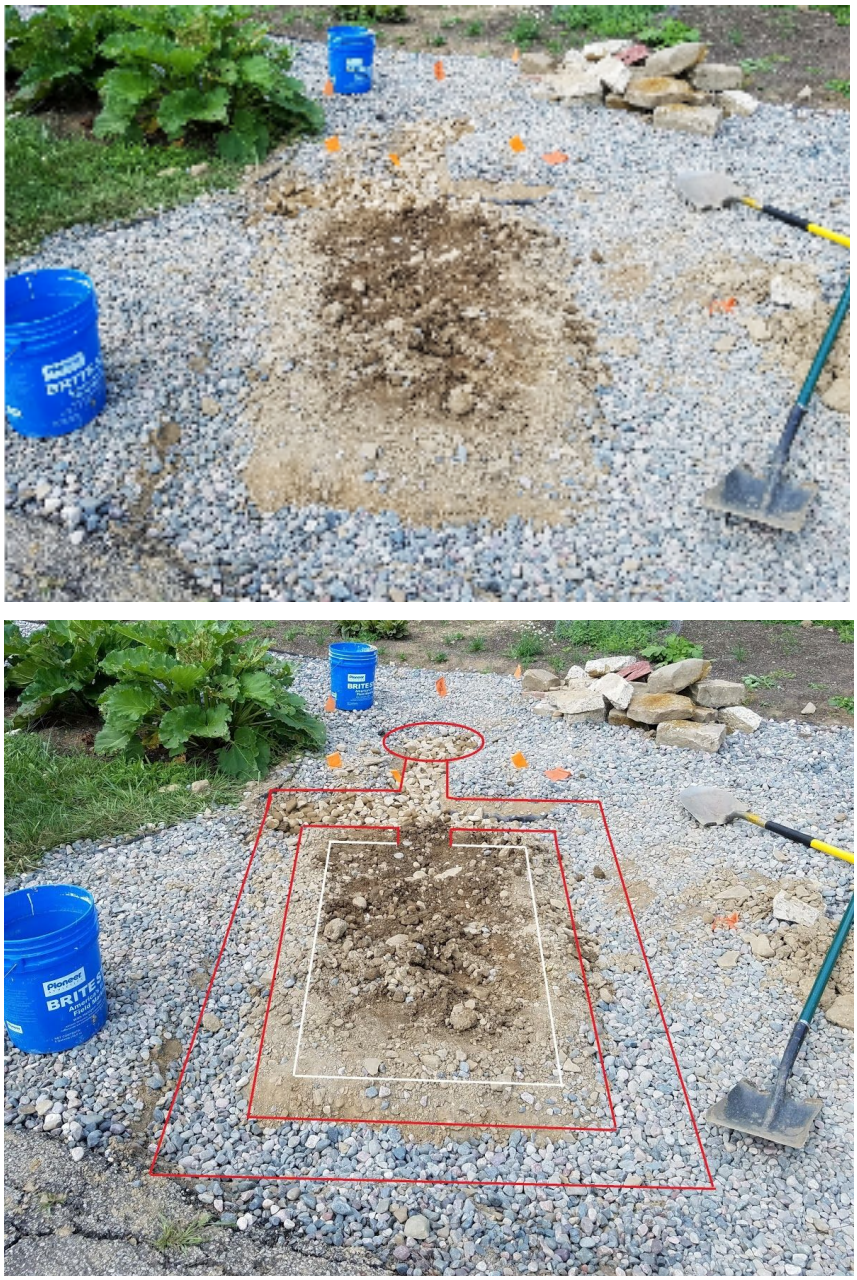


Figure 7. **Top:** Backfilling the trench with gravel and tamping it down so as to prevent it from moving in the future.
Bottom: The red lines delineate the trench and the white lines represent the future foundation and stem wall.

Drainage under the stem wall included digging a 5ft long by 2.5ft wide by 1ft deep pit. This was filled with the pre-existing gravel until the gravel layer rested 4 inches below surface level. I tamped down the gravel, so that the stem wall would not shift later. I connected the drainage under the stem wall with the trench only on the right

side--just in case if some water went under the stem wall would be able to leave and go towards the hole. The trench and hole were all filled with the pre-existing gravel and tamped down.



Figure 8. The beginning of the drainage system under the stem wall before the tamped gravel and stone. Excavated dirt to the left. Red lines delineate the trench.

I created the stem wall by arranging and cementing a number of natural stones, reclaimed concrete, and pea-size gravel. To create a relatively flat base, I used tiles I found at Robertson Field as the first layer of my stem wall.



Figure 9. The first layer of stones before mortar was applied. Tamped gravel is underneath.

I mixed Quikrete brand type-N cement mortar by putting one bag of mortar into a black mixing tub, adding the required amount of water (around 4 pints), and mixing until the desired consistency. I then shoveled this mortar overtop the tiles/first layer of stone I had placed. For the next layer, I picked the largest natural stones that I found from Robertson Field and put them on the outside. I picked large reclaimed concrete (urbanite) pieces to go in the middle, as I only wanted natural stone to be visible.



Figure 10. A layer of stones with cement mortar in the joints. Notice the reclaimed concrete piece in the center right.

I walked over these unmortared stones to see areas in which they shifted when weight was put on them. If they moved, I put smaller stones in areas that gapped. If that didn't work, I used the metal chisel to chip away at areas that were causing the stones to be unstable. Between the big stones, I put pea-size gravel. I mixed another bag of concrete and applied the mortar below and between all of the rocks of the second layer. After the second layer was finished, I let it dry for a day. I repeated the same steps of picking stones, determining how stable they were and adjusting them if they weren't by wedging smaller stones in the gaps for 5 layers of stone in total. I then threw pea-size gravel to fill in any smaller crevasses between larger stones.



Figure 11. Continuing the process of mortaring continual layers of natural stone and reclaimed concrete with cement mortar.

Before I finished applying mortar to the final layer of stones, I began making the wooden frame for the back of the bench. This was done by finding a dry log that was roughly the same length of the bench, and then screwing five 2x2x36in pressure-treated wood stakes at even intervals, perpendicular to the log. I placed this log between a thinner layer of stones on the outside and thicker stones that would become the seat. I added pea-size gravel and mortared the log in with the stones for stability. This was the final layer of stones added to the bench, and they helped stabilize the bench's back

frame. This is shown in the bottom picture of *Figure 12*. Once these layers were dry, I used the chisel and 100 grit sandpaper to detail the mortar joints that were very rough, had too much mortar, or were aesthetically unappealing.



Figure 12. **Top:** Beginning to make and place the frame for the back of the bench.
Bottom: The frame freshly cemented into the base for stability. Another layer of rocks was added on top of the log holding the back frame.

Making a Frame

Cob projects typically have a frame of some sort. In the case of a cob bench, the frame comes into the play for the back. Frames help a cob project by giving it a structure which cob can cling to. To make this frame, I screwed another 2x2x36in board horizontally across the 5 vertical boards I had cemented into the stem wall. This horizontal board was roughly 10 inches above the stone seat of the bench. I then used a hand saw to shorten another 2x2x36in board until it only crossed the three vertical boards in the middle of the bench, and screwed it in about 14 inches above the first horizontal board.

I used the saw to cut the vertical boards above the topmost horizontal board. In this way, the outer edges of the back of the bench were lower than the middle. After the wooden frame was finished, I began placing recycled wine and beer bottles vertically against the wooden frame. These bottles are useful in that they act as filler material so less cob is used. The rationale behind placing the bottles vertically was simply because it was easier to keep them from moving while I was later applying the chicken wire around the frame.





Figure 13. The bench and frame after the horizontal bars were added and the vertical bars were sawn to size.

After I finished placing the first layer of bottles on the stone seat, I wrapped metal chicken wire horizontally around the metal frame and stapled it into the back of the vertical wooden boards. The chicken wire was added in order to further stabilize the bottles against the frame, as well as giving the cob more surface by which to adhere. I made sure to not fully enclose the bottles and the wooden frame, as I still needed to add a second layer. I began adding a second layer of bottles that rested in between the chicken wire and sat on top of the lowest horizontal wooden bar, seen in *Figure 15* below. Because I wanted the top of the back portion of the bench to be curved, I cut and shaped the chicken wire to do so. In this portion of the wire, bottles were laid more horizontally to follow with the frame made by the chicken wire.



Figure 14. Continuing the bench back frame by adding recycled glass bottles as filling material.

Once all of the glass bottles were in place, I finished stapling the chicken wire to the front of the wooden boards. In places where there was a lot of blank space, I found rocks of similar sizes to fill in between the bottles. For extra stability, I ran metal wire around each individual bottle and the nearest vertical or horizontal board. Then I brought both ends of the metal wire together and twisted them tightly, like a twist tie at a grocery store. The rationale behind this is I wanted my frame to be as stable as possible when applying the cob, so as to minimize cracks when drying.







Figure 15. **Top:** The finished frame filled with recycled glass bottles and rocks as filling material.
Middle: A view of the finished frame from the back.
Bottom: A close-up view of the twisted ends of metal wire going around each of the glass bottles.

Testing the Cob Mix

Because each soil sample is variable, it is incredibly important to test ratios of the soil being used by making cob test batches. This is typically done by performing a ball test where one mixes the clay and sand they have in different ratios, compacts them tightly into a ball, and then drops it from waist height and see how the ball changes. The rationale behind this test was to see how well the clay stuck the sand particles together. If there was too much clay, the ball would deform when it hit the ground. If there was too much sand, the ball would crumble apart. If the ball had a good mix of clay and sand, it would mostly retain its shape when it hit the ground. To begin this test, I first combined the two different types of powdered clay I had together: 1 part hawthorne clay to 1 part OM4 ball clay. I wore a mask any time I was working with the powdered clay or sand as they are fine particulate material and not healthy to inhale.

I tried three different proportions of sand and clay. **Ball 1** was 2 parts clay (half hawthorne, half ball clay) to 3 parts sand. **Ball 2** was 1 part clay, 3 parts sand, and **ball 3** was 1 part clay, 2 parts sand. To mix these materials together, I first added the powdered clay and sand to a small circular tupperware contained and mixed it with a spoon. After it was properly mixed (i.e. I could not distinguish the clay from the sand), I started adding very small amounts of water and mixing until the clay began holding the sand together.







Figure 16. **Top Left:** A ball mixture before adding water.
Top Right: The first ball to be tested.
Bottom: Results of the ball test. Ball 1 is on the left, Ball 2 is in the middle, and Ball 3 is on the right.

Afterwards, I took the mixture out of the plastic container and tightly squeezed it into a ball in my hands. I did this to all three balls before I started dropping them from waist height. When I dropped each ball from waist height, ball 1 deformed on impact, ball 2 crumbled apart, and ball 3 deformed less than ball 1. This was an unusual outcome, as both cob books said the ball would hold its shape. Even though ball 3 (1 parts clay to 2 parts sand) deformed on impact, it deformed less than ball 1 (2 parts clay to 3 parts sand), so I used ball 3 proportions for my cob mix.

Mixing the Cob

Cob mixing can be done in many different ways: using a cement mixer, having horses trample the mix, or by tarp. The traditional method, and one which has the least amount of environmental impact is the tarp method that I chose. First, I put down one of my grey 10ft by 7ft tarps onto the grass adjacent to my work area. In a five gallon bucket, I began mixing roughly 10 garden trowels worth of powdered clay to 20 garden trowels of all-purpose masonry sand, following the proportions of the test batch. The sand was purchased from The Home Depot. I mixed this while wearing a n-95 dust mask because fine particulates would fly into the air while working.



Figure 17. Dry cob mix on the tarp.

After the clay and sand were mostly mixed, I would dump it on the tarp and mix it with my hands, as it usually didn't fully mix in the bucket. When the dry mix was on the tarp, I pulled up the sides of the tarp to pile the mix in the middle. I would dig a large 'X' into the dry mix, to better help water disperse. For a 10 trowel clay mix, I estimate I used between 1/4 of a 5 gallon-bucket's worth of water.



Figure 18. Adding the water to the dry cob mix.

To mix the water into the powdered clay and sand, I grabbed two corners of the tarp and began stomping my bare feet into the mix. If certain parts looked drier than others, I would take the section of the tarp closest to the dry portion and lift it up so it

came closer to the area I was mixing with my feet. Unfortunately, there is no technical way to explain when a cob mix is adequately wet or dry. It needs to be dry enough to form with your hands, but wet enough that it doesn't crumble apart. This is why it is ***strongly*** suggested to go to a few workshops before undertaking a cob project.



Figure 19. Stomping the cob with added straw using the tarp method.

After the cob reached the correct consistency, it was time to add the winter wheat straw Kerstin Martin had grown over the summer at the MARC Community Garden. I would pick two handfuls of 10in long dry straw that I had cut and sprinkled them on the mix as I stomped on it. I kept stomping and pulling up the tarp to flip the increasingly coalescing cob mix, specifically targeting the pieces of straw that didn't have any of the mix on it. The mix was done when I could lift the tarp up and make the mix into a burrito shape.

At this point, I began cobbing my bench. This was done by picking up two handfuls of the cob mix and pushing it into the bottom of the chicken wire and wood frame of the back, where the frame met the stone seat. To better attach the cob and to help it dry, I pushed it into the chicken wire frame with my thumbs. In this way, the straw within each cob lump that I have attached threaded into future cob lumps that I put over the original. Leaving the thumb prints also allowed the cob to dry faster. After the bottom

portion of the frame was finished, I covered the entire bench with one of the grey tarps to protect the cob from any potential rain.



Figure 20. Cob applied to the bench frame.

The next day, I repeated the process of making and applying cob batches until the frame was covered and I could no longer see the chicken wire. I tarped the bench when I was done for the day and let it dry.





Figure 21. **Top:** A view of the back of the bench after the first day of applying cob.
Bottom: A view of the front of the bench after the first day. Notice the thumb prints in the cob.

I added another layer of cob the next day, until there was roughly 2 to 3 inches of cob on top of the frame. After I finished the cob, I covered the bench with a tarp and waited 4 days until the cob was completely dry before applying plaster. To assist with drying, I would uncover the bench around noon every day and let it dry in the sun for roughly 4 to 5 hours.





Figure 22. **Top:** A picture of the back of bench with the final layer of cob added. **Bottom:** A picture of the front of my bench.

Making a Plaster

Even after cob is dry, it is still made out of porous clay. The clay would lose its structural integrity if it were to get wet for a period of time. For that reason, plasters and protections are necessary. The plaster for my bench was simply another layer of a smoother, finer cob mix with smaller sand grains and cellulose as the binding fiber instead of straw. The plaster needed to be smoother for a number of reasons: it would be more comfortable for those who would be resting against the bench, as well as the smooth layer helping to prevent water damage because it doesn't have cracks (Weismann & Bryce, 2007; Evans, Smith, & Smiley, 2002). If water was to get into cracks, it could begin to saturate the cob and disrupt its structural integrity. In the winter, if cracks were present and water was to enter and then freeze, this would further damage the cob because of water's expansion upon freezing. For these reasons, it is very important to have as few cracks as possible.

To make this plaster, I mixed it the same way as the original cob mix with four exceptions: first, I substituted the original sand for the finer, screened sand. Second, I dyed the water used in the mix with a full bottle of terracotta red cement dye. Third, instead of using straw as the fiber to hold the cob together, I used cellulose fiber. Finally, the plaster mix was slightly wetter than the original cob mix. To get a finer sand, I simply screened the all-purpose sand with a cooking strainer to remove the coarser grains.



Figure 23. **Top Left:** A look at the plaster mix before adding it onto the cob. Notice the grey cellulose fiber on the arm.
Top Right: Applying the plaster. The cooking strainer shown was used to help sift out the coarser grains of sand.

Bottom: A closer look at the plaster.

To apply the plaster, I put it in my hand and then smeared it across the top of the cobbed frame with the flat of my palm. I continued to do this until the vertical halves of the front and back of the frame were covered. I let the plaster dry slightly before taking a paint brush, dipping it in the dyed water, and lightly brushing it over the plaster I applied to the frame. This served to both smooth the plaster and increase its color, shown in *Figure 24* below. The dyed water I was using was left over from mixing batches of plaster. I continued mixing and applying the plaster until the entire frame was covered ½ inch to 1 inch deep. I then continued to use the paintbrush and dyed water to smooth the plaster and give it extra color.





Figure 24. **Top:** A view of the plaster as it begins to dry. The right handed portion has been painted over with the dye to smooth the surface of the plaster and give it more color.

Bottom: Painting the plaster. The broken pieces of glass on the seat will later become the mosaic.

After the plaster was finished, I brushed boiled linseed oil over top of it to make the cob even more water resistant. This process is fully detailed below because it occurred after adding the decorations to the cob.

Decorating the Cob

Most cob projects have multiple points of artistic expression. Since the cob is applied by hand and is made with clay, it is very pliable and can be shaped in many different and creative ways. Another common practice is to decorate cob with mosaics made of glass, which I did. While the plaster was drying, I began making a broken glass mosaic on the front of my bench with recycled glass bottles. The majority of the bottles had labels. The best way to remove them involved soaking them in water for a few hours and then ripping them off. They usually didn't rip off perfectly, so I used a wire brush to both scratch and scrape off the rest of the label.

I separated the newly cleaned bottles by color. In another 5 gallon bucket, I used the metal chisel to smash them into pieces while wearing safety goggles and gloves. I picked a variety of shapes and colors for the broken bottle pieces. I prioritized ones that were more flat. Just in case the edges were sharp, I used 100 grit sandpaper to soften the edge of each piece of broken glass.



Figure 25. A view of the broken glass pieces before they became the mosaic.

Before placing the broken glass into the slightly damp plaster of the back of the bench, I made sure the plaster was wet enough that it would accept something pressed into it, but not so wet that it would ruin the plaster. I placed the glass pieces with the curvature side into the plaster. They needed to be cleaned afterward. Once the glass pieces were set, I used the paintbrush and dyed water to smooth out the cracks around the glass pieces. I let the plaster dry for two days.



Figure 26. The bench after the mosaic was made.

Once the plaster was dry, I began painting layers of boiled linseed oil on the back of the bench to further help protect the cob from water and any possible liquids people might spill while sitting there. It is a common fact that oil and water do not mix, and the linseed oil made the cob be more water resistant than just having the plaster itself.

To apply the oil, I cleaned the paint brush that I painted the dye with and used it to paint the bench. This was a slow process because linseed oil is combustible in large quantities. Layers of linseed oil needed to be thin, or otherwise they would have become sticky. I waited a day after each layer was applied to let it dry. In total, I painted five layers of linseed oil.



Figure 27. The finished bench.

Notes After Building

I had to make many concessions in materials from lack of time, lack of experience, lack of money, or lack of the material itself. For example, the two books on cob that I used suggested making a lime mortar versus a concrete mortar because it was more environmentally friendly (Weismann & Bryce, 2007; Evans, Smith, & Smiley, 2002). Unfortunately, lime mortar is caustic. I didn't feel comfortable using it without any experience. For that reason, I used the cheaper, safer, and easier cement mortar.

Similar events happened with both the sand and clay. Because I couldn't find soil around my site that had enough clay, I was forced to get powdered clay from Allegheny College's art department and buy my own coarse sand. I tried every trick suggested in both books--calling excavation contractors, looking for valleys and cut river banks with

skunk weed, looking for areas in which the ground looked dry and cracked--but the vast majority simply held a lot of silt and next to no clay.

Creating a Life Cycle Assessment (LCA)

To create my LCA, I first needed to record the materials that I would include. Tools were not included in the environmental impact unless I needed to purchase them myself. Materials which were given to me second hand after already being used (e.g. glass bottles given to me, reclaimed concrete, natural stone found at Roberston, etc) were not included, as their original environmental impact was already taken by the original user. The materials included and excluded are shown in table 1 below. The boundaries of this particular LCA was from cradle to site, meaning all materials were included up until the point where each bench would be constructed on site.

Table 1 - Materials Included and Excluded in Cob Bench LCA

Materials Not Counted for Environmental Impact	**Materials Counted for Environmental Impact**
Natural stone	Powdered OM4 Ball Clay
Reclaimed concrete	Powdered Hawthorne Fire Clay
Winter wheat straw	Gravel
5 gallon buckets	All-purpose sand
Glass bottles	Cement mortar type N
	Pea-size gravel
	Phosphate-coated steel drywall screws
	Galvanized steel staples
	Galvanized steel chicken wire
	Galvanized metal wire
	Cement dye

	Pressure-treated wood
	Cellulose fiber
	Sandpaper
	Masks
	Boiled linseed oil
	Treated water
	Plastic tarp
	Gasoline

For the materials for which I would consider in this LCA, I recorded or calculated their weights and put them in a chart within the results section of this study. The values I compared included embodied energy (EE) in MJ/kg, embodied carbon (EC) in kg CO_2/kg, and cost. Embodied energy is a value highlighting how much total energy was used in making any material or product. Embodied carbon is a similar type of value, but explains how much total carbon was used in making a product.

To perform these calculations, I counted or estimated how much material was used and then found the weight of the entire product form Home Depot's website. For example, I used 13 phosphate-coated steel drywall screws and found that a box of 166 of these screws equalled 1 lb. From there, I found the weight per individual screw, converted it into kg/screw, and then multiplied by the number of screws I used. This sample calculation is below.

$$\frac{1\ lb}{166\ drywall\ screws} = 0.006\ lbs/drywall\ screw$$

$$\frac{0.006\ lbs}{1\ drywall\ screw} \times \frac{0.453\ kg}{1\ lb} = 0.0027\ kg/drywall\ screw$$

$$13\ drywall\ screws \times \frac{0.0027\ kg}{1\ drywall\ screw} = 0.035\ kg$$

From there, EE and EC values needed to be found. I gathered most of this data from a source from Jones (2011), or Carnegie Mellon University's EIOLCA tool (Carnegie Mellon University Green Design Institute, 2016). To calculate the specific

amount of embodied energy or embodied carbon any of my materials have, I multiplied the weight (in kg) by both EE value (in MJ/kg) and EC value (in kg CO_2/kg) separately. An example calculation is listed below.

Embodied energy of sand:

$$90.7\ kg\ sand \times \frac{0.081\ MJ}{1\ kg\ sand} = 7.35\ MJ$$

Embodied carbon of sand:

$$90.7\ kg\ sand \times \frac{0.0048\ kg\ CO2}{1\ kg\ sand} = 0.435\ kg\ CO2$$

Because my LCA included transportation, I needed to calculate how much gasoline I used. To do so, I recorded the number of miles I drove while making my bench and then divided that number from the total MPG of my car, a 2012 Nissan Sentra. This provided the number of gallons of gas used. Afterwards, I converted the gallons into kilograms, and then from kilograms into the separate EE and EC values. The conversion factor from gasoline to kilograms was provided by Reference.com. The calculation was as follows:

$$201.5\ miles \times \frac{1\ gallon\ gasoline}{25\ miles} = 8.06\ gallons$$

$$8.06\ gallons\ gasoline \times \frac{2.78\ kg\ gasoline}{1\ gallon\ gasoline} = 22.4\ kg\ gasoline$$

$$22.4\ kg\ gasoline \times \frac{43.1\ MJ}{1\ kg\ gasoline} = 965.4\ MJ$$

$$22.4\ kg\ gasoline \times \frac{8.9\ kg\ CO2}{1\ kg\ gasoline} = 199.4\ kg\ CO2$$

Costs for treated water was gathered from Allegheny College's infrastructure data for the academic buildings (Allegheny College, 2013). Embodied energy and embodied carbon values were found from Carnegie Mellon University's EIOLCA tool (2016).

I compared the EE, EC and cost of my bench to the same categories of two other benches available for purchase online. Both were made of conventional materials: one was made of aluminium and one of hardwood. I picked these two benches for their

similarity in size to my bench (Sears, 2016; Innova, 2016). My bench had dimensions of L 54in x W 24in x H 39in. The wooden Sears' bench hasd dimensions of the following: L 57in x W 24in x H 34in, and the aluminium bench by Innova had dimensions of L 51in x W 24.3in x H 33in. To get the EE and EC numbers for the materials of these benches, the weight of each material in kg was multiplied separately by the EE value (in MJ/kg) and the EC value (in kg CO_2/kg). All materials listed for these benches were included in their respective LCAs, as well as an added theoretical concrete footer and individual transportation calculations.

Theoretical Concrete Foundations for the Innova Aluminium and VIFAH Hardwood Benches

If the MARC were to buy the Innova aluminium bench or the VIFAH hardwood bench instead of my bench, they would have to install a concrete foundation for both of them to have a stable base for which the bench would rest upon (Concrete Network, 2014). A concrete footer would also be needed in order to protect the theoretical benches from groundwater.

Concrete foundations need a gravel subbase underneath to create a stable base (Concrete Network, 2014). To create calculations for each theoretical foundation, general bench dimensions were found to be 10" to the total length of the bench--5" on each side--and 8" on the width--4" on each side (City Council of Fremont, 2011). The depth of both the gravel and concrete levels would be 4" each (City Council of Fremont, 2011). For the Innova aluminium bench, each one of these levels were calculated to be 4.56 ft^3. This would require roughly 7.6 80lb bags of concrete, or 608lbs (Sakrete). The calculation for gravel was a little more extensive: 1" to 2" gravel is 4000lbs per cubic yard, and 4.56 ft^3 is 0.17 cubic yards, or 680lbs of gravel (Russo Development, 2011).

VIFAH's hardwood bench would need 4.96 ft^3 of both concrete and gravel. Therefore, 8.3 80 lb bags of concrete would be needed, or 664 lbs (Sakrete). 4.69 ft^3 is

0.18 cubic yards, which means this bench would require 720 lbs of 1” to 2” gravel (Russo Development, 2011).

Theoretical Transportation Calculations for the Innova Aluminum and VIFAH Hardwood Benches

To create calculations for both the aluminium and hardwood benches, the first step was to find their point of origin. The acacia hardwood bench is manufactured and shipped from Vietnam--most likely from Ho Chi Minh City (Russell, 2005). Innova’s Metro aluminium bench is manufactured and shipped from Yantian, China (Innova, 2016). Since these are both overseas locations, they would be transported via cargo ships.

To make a calculation for how much cargo ships emit per ton per mile, the fuel and its efficiency first needed to be identified. These ships use heavy fuel oil (HFO), which emitted 3.01 kg CO_2 per liter in 2006 (New Zealand Ministry of the Environment, 2015). 1 US gallon of HFO produces an average of 150700 BTUs (Engineering Toolbox). Cargo ships use 571 BTUs per ton mile (Pew Center Climate and Energy Solutions, 2010). The equation for finding the amount of CO_2 equivalent (e) per ton mile looked like the following:

Cargo Ship - Heavy Fuel Oil (HFO):

$$\frac{150700\ BTU}{1\ US\ Gal\ HFO} \times \frac{1\ US\ Gal\ HFO}{3.7854\ Liters\ HFO} = \frac{39810.747\ BTU}{1\ Liter\ HFO}$$

$$\frac{1\ Liter\ HFO}{39810.747\ BTU} \times \frac{3.01\ kg\ CO2\ e}{1\ Liter\ HFO} \times \frac{571\ BTU}{1\ ton\ mile} = \frac{0.0432\ kg\ CO2\ e}{1\ ton\ mile}$$

Therefore, cargo ships produce 0.0432 kg CO_2 equivalent per ton mile.

A similar calculation needed to be produced for bench transportation via semi-trailer trucks, as accounting for cargo ships only transports the benches to a coastal port location. A direct shipping route from Vietnam or China was unable to found, so the assumptions used in these calculations are that the route with the least amount of nautical miles would be used. This would cause the benches to be shipped to the west coast (Sea-Distances.org). Semi-tractor trailers were also used in these

calculations instead of trains or other forms of transportation as to further decrease the number of miles travelled.

Semi-tractor trailers use diesel fuel which creates 139000 BTUs per US gallon, as well as emitting 2.68 kg CO_2 equivalent per liter (Engineering Toolbox; New Zealand Ministry of the Environment, 2015). In addition, semi-tractor trailer's energy use per ton mile is 4074 BTUs (Pew Center Climate and Energy Solutions, 2010). Therefore the equation to find kg CO_2e produced per ton mile would look like the following:

Semi-Tractor Trailer - Diesel:

$$\frac{139000\ BTU}{1\ US\ Gal\ Diesel} \times \frac{1\ US\ Gal\ Diesel}{3.7854\ Liters\ Diesel} = \frac{36720.03\ BTU}{1\ Liter\ Diesel}$$

$$\frac{1\ Liter\ Diesel}{36720.03\ BTU} \times \frac{2.68\ kg\ CO2\ e}{1\ Liter\ Diesel} \times \frac{4074\ BTU}{1\ ton\ mile} = \frac{0.297\ kg\ CO2\ e}{1\ ton\ mile}$$

Therefore, an item transported by truck would cause emissions of 0.298 kg CO_2e per ton mile.

The next step involved researching different possible trade routes. For the VIFAH hardwood bench, the point of shipping would most likely be Ho Chi Minh city in Vietnam, whereas Innova is Yantian, China (Innova, 2016; Import Genius, 2017). VIFAH and Innova would most likely ship to Seattle because it is the shortest distance versus trying to ship it to New York City (Sea-Distances.org). From Ho Chi Minh City to Seattle was 6,590 nautical miles, and Hong Kong to Seattle was 6,044 nautical miles (Sea-Distance.org). Hong Kong was used in place of Yantian's port, as that did not exist in Sea-Distances' database. From Seattle, the benches would have to travel 2,511 miles by semi-trailer truck to get to the MARC site (Google Inc.).

To figure out how much energy was used and emissions created for the transportation, another calculation is necessary. First, BTUs per ton mile were converted to MJ per ton mile to get a value of cargo ships at 4.3 MJ per ton mile, and semi-trailer trucks at 0.6 MJ per ton mile. Nautical miles were converted into miles to be able to cancel units of ton miles in the future. Next, tons were multiplied individually by both miles by ship and miles by truck to get respective ton miles for each mode of

transportation. The first calculation was for the VIFAH hardwood bench, from Ho Chi Minh City, Vietnam to Seattle, USA.

Calculations from transportation for VIFAH hardwood bench:

Energy use and CO_2 emissions created from the cargo ship:

$$0.0149\ tons \times 6590\ nautical\ miles \times \frac{1.15078\ miles}{1\ nautical\ mile} = 112.966\ ton\ miles$$

$$112.966\ ton\ miles \times \frac{571\ BTU}{1\ ton\ mile} \times \frac{1\ MJ}{947.817\ BTU} = 68.05\ MJ$$

$$112.966\ ton\ miles \times \frac{0.0432\ kg\ CO2\ e}{1\ ton\ mile} = 4.88\ kg\ CO2\ e$$

Energy use and CO_2 emissions created from the semi-tractor trailer:

$$0.0149\ tons \times 2511\ miles = 37.41\ ton\ miles$$

$$37.41\ ton\ miles \times \frac{4.3\ MJ}{1\ ton\ mile} = 160.86\ MJ$$

$$37.41\ ton\ miles \times \frac{0.297\ kg\ CO2\ e}{1\ ton\ mile} = 11.11\ kg\ CO2\ e$$

Therefore, the total energy use caused by transportation for the VIFAH hardwood bench was 228.91 MJ whereas the total CO_2 emissions were 15.99 kg CO_2e. The same type of calculations were performed for Innova's aluminium bench, which would ship from Hong Kong, China to Seattle, USA.

Calculations for transportation for Innova aluminum bench:

Energy use and CO^2 emissions from the cargo ship:

$$0.023\ tons \times 5740\ nautical\ miles \times \frac{1.15078\ miles}{1\ nautical\ mile} = 151.93\ ton\ miles$$

$$151.93\ ton\ miles \times \frac{0.6\ MJ}{1\ ton\ mile} = 91.15\ MJ$$

$$151.93\ ton\ miles \times \frac{0.0432\ kg\ CO2\ e}{1\ ton\ mile} = 6.56\ kg\ CO2\ e$$

Energy use and CO_2 emissions from the semi-tractor trailer:

$$0.023\ tons \times 2511\ miles = 57.753\ ton\ miles$$

$$57.753\ miles \times \frac{4.3\ MJ}{1\ ton\ miles} = 248.34\ MJ$$

$$57.753\ miles \times \frac{0.297\ kg\ CO2\ e}{1\ ton\ miles} = 17.15\ kg\ CO2\ e$$

To determine which one was the most environmentally friendly, I looked at the total embodied carbon (EC) values of all three benches. The one with the lowest EC value was the one which had the least amount of impact on the environment. I will make charts and graphs visually depicting how each bench compares with the other benches on all three categories of EE, EC, and cost.

Results:

Results will be divided into five different sections: 1) the master list of all material values found to conduct this LCA, 2) the values for the cob bench, 3) the values for Innova's aluminum bench, 4) the values for VIFAH's hardwood bench, and 5) a comparison of all three benches and their respective values.

Master List of Embodied Energy, Embodied Carbon, and Cost Values for Materials in All Three Benches

Table 2 below is a master list of materials and their values of embodied energy, embodied carbon, and cost per kilogram or per unit. This chart is meant to help future cob builders understand the environmental impact of their materials. It was composed because there was significant difficulty in finding some of the values, such as the values for clay. In terms of this study, table 2 was used to organize and record the values by which I needed to multiply in order to get the exact EE, EC, and cost values for each bench.

Table 2 - Master Embodied Energy + Embodied Carbon + Cost Table

Material	**Embodied energy (EE) MJ/kg[f]**	**Embodied carbon (EC) kgCO_2/kg[f]**	**Cost USD[e]**
Combined Clay* (Powdered Old Mine #4 and Powdered Hawthorne Fire Clay)	ND	0.906 kgCO_2/kg	$17/50lb bag OM4 $18/50lb bag Hawthorne[l]
Gravel/pea-size gravel	0.083 MJ/kg	0.0048 kgCO_2/kg	$0.06/kg
All-purpose sand	0.081 MJ/kg	0.0048 kgCO_2/kg	$3.55/50lb bag

Cement mortar type N	1.11 MJ/kg	0.163 $kgCO_2$/kg	$4.90/60lb bag
Concrete (4000psi/28mPa)	0.78 MJ/kg	0.106 $kgCO_2$/kg	$4.15/80lb bag
Phosphate-coated steel drywall screws	28.50 MJ/kg (average world recycled content)	1.92 $kgCO_2$/kg	$9.47/1lb box of 182 screws
Galvanized steel staples	28.50 MJ/kg	1.92 $kgCO_2$/kg	$3.22/box of 1,250 staples
Galvanized steel chicken wire	28.50 MJ/kg	1.92 $kgCO_2$/kg	$15.42/ 1inx3ftx25ft roll
Galvanized steel wire	28.50 MJ/kg	1.92 $kgCO_2$/kg	$6.29/14 gauge x 100ft roll
Cement dye	ND	ND	$5.93/10 oz. container
Pressure-treated wood stakes****	10 MJ/kg	ND	$19.77/16 pack
Cellulose fiber	2.12 MJ/kg	ND	$11.25/19 lb bag
100 grit sandpaper	ND	ND	$3.97/3-2/3inx9in 6-sheet packet
N95 Respirator Masks	ND	ND	$37.82/case of 24 masks
Boiled linseed oil	59 MJ/kg[g]	0.75 $kgCO_2$/kg[g]	$7.98/quart
Treated water**	0.04 MJ/gallon[i]	0.0054k $kgCO_2$/kg[i]	$0.01/gallon[h]
Plastic tarp (Polyethylene)	83.10 MJ/kg	2.07 $kgCO_2$/kg	$10.97/8x10 silver heavy-duty tarp
Gasoline***	43.1MJ/kg	8.9 $kgCO_2$/kg	$2.16/gallon (August 2016 price)[c]
Aluminum	159 MJ/kg	8.28 $kgCO_2$/kg	$0.79/lb or $1.74/kg[a]
Stainless steel nuts	56.7 MJ/kg	1.676 $kgCO_2$/kg	$0.32/nut[b]
Stainless steel bolts	56.7 MJ/kg	1.676 $kgCO_2$/kg	$8.75/box of 25
Acacia hardwood	7.8 MJ/kg	0.128 $kgCO_2$/kg	ND
Heavy fuel oil (HFO)	4.3 MJ/**ton mile**[k]	0.0431 $kgCO_2$e/**ton mile**	ND
Diesel	0.6 MJ/**ton mile**[k]	0.297 kg CO_2 e/**ton mile**	ND

ND = No Data
*These combined values of clay come from Carnegie Mellon University's Green Design Institute EIOLCA tool (2016).
**Values from http://seafood.oregonstate.edu/.pdf%20Links/Embodied-Energy-and-Energy-Analysis-of-Wastewater-Treatment-Using-Wetlands.pdf
***Values from http://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=2019&context=etd

****Numbers here are taken from average EE and EC for general lumber from Jones (2011). Values for pressure-treated wood were not found.
[a]Price from http://www.infomine.com/investment/metal-prices/aluminum/
[b]Price from http://www.homedepot.com/p/Everbilt-5-16-in-Stainless-Steel-Hex-Nut-804886/204647951
[c]Price from U.S. Energy Information Administration (2017)
[d]This is a lower value because info could only be found for part of the clay making process (US EPA, 1994)
[e]Prices from Home Depot website (2016) unless otherwise specified
[f]EE and EC values come from Jones (2011) unless otherwise specified
[g]Values from Häkkinen et al., 1999.
[h]Prices from Allegheny College. (2013). [Allegheny College Water Bill Data]. Unpublished raw data.
[i]Values come from Carnegie Mellon University Green Design Institute EIOLCA tool (2016).
[k]Values from Pew Center Climate and Energy Solutions (2010).
[l]Price from www.sheffield-pottery.com

Cob Bench Results

The cob bench cost $212.13. It had an embodied energy value of 1456.4MJ and an embodied carbon value of 259.4kg CO_2. All of the material values of this bench are shown in Table 3 below. Of the materials with recorded embodied carbon values, galvanized steel staples contributed the least (0.0086kg CO_2) whereas gasoline contributed the most (199.4kg CO_2), seen in both *Figure 29* and Table 3 below. The galvanized steel staples also had the lowest embodied energy value (0.0128MJ) whereas gasoline had the highest value at 965.4MJ. Gravel was the most expensive and also heaviest material used in bench construction. It cost $81.38, comprising 38% of the total cost of the bench.

Table 3 - LCA for the Cob Bench

Material	**Weight/amount (Colao, 2016)**	**Embodied energy (EE) MJ**	**Embodied Carbon (EC) kg CO_2**	**Cost USD[a]**
Clay combined* (Powdered OM4 + Hawthorne Clay)	31kg	ND	28.1kg CO_2e	$23.91
Gravel	1191kg	98.85MJ	5.72kg CO_2	$81.38
All-purpose sand	90.7kg	7.35MJ	0.435kg CO_2	$14.20
Cement mortar type N	122.5kg	135.98MJ	19.97kg CO_2	$26.50
Pea-size gravel	22.6kg	1.88MJ	0.108kg CO_2	$4.20

Phosphate-coated steel drywall screws	0.035kg	1.00MJ	0.067kg CO_2	$0.74
Galvanized steel staples	0.0045kg	0.0128MJ	0.0086kg CO_2	$0.08
Galvanized steel chicken wire	0.33kg	9.41MJ	0.63kg CO_2	$1.89
Galvanized metal wire	0.418kg	11.9MJ	0.803kg CO_2	$3.15
Cement dye	10 oz	ND	ND	$5.93
Pressure-treated wood	6.15 stakes (4.7kg)	47MJ	ND	$7.60
Cellulose fiber	0.454kg	0.96MJ	ND	$0.60
Sandpaper	1 sheet	ND	ND	$0.66
Masks	3 masks	ND	ND	$4.73
Boiled linseed oil	1 quart (0.88kg)	51.9MJ	0.66kg CO_2	$7.98
Treated water	20 gallons (75.7kg)	0.08MJ	0.409kg CO_2	$0.20
Plastic tarp	8ft x 10ft tarp (1.50kg)	124.7MJ	3.11kg CO_2	$10.97
Gasoline	8.06 gallons (22.4kg)	965.4MJ	199.4kg CO_2	$17.41
Total	N/A	**1456.4MJ**	**259.4kg CO_2**	**$212.13**

*****These combined values of clay come from Carnegie Mellon University's' EIOLCA tool.
[a]Prices come from Home Depot's website unless otherwise stated in Table 1
ND = No Data

By far, gasoline had the highest embodied carbon and embodied energy values by a very large margin. It contributed 965.4MJ and 199.4kg CO_2, seen in *Figure 28* and *Figure 29* below. Gasoline encompassed 66% of the total embodied energy and 77% of the total embodied carbon of the bench. The combined clay value was the second highest for embodied carbon, producing 28.1kg CO_2. Cement mortar N was the second highest embodied energy value at 135.98MJ.

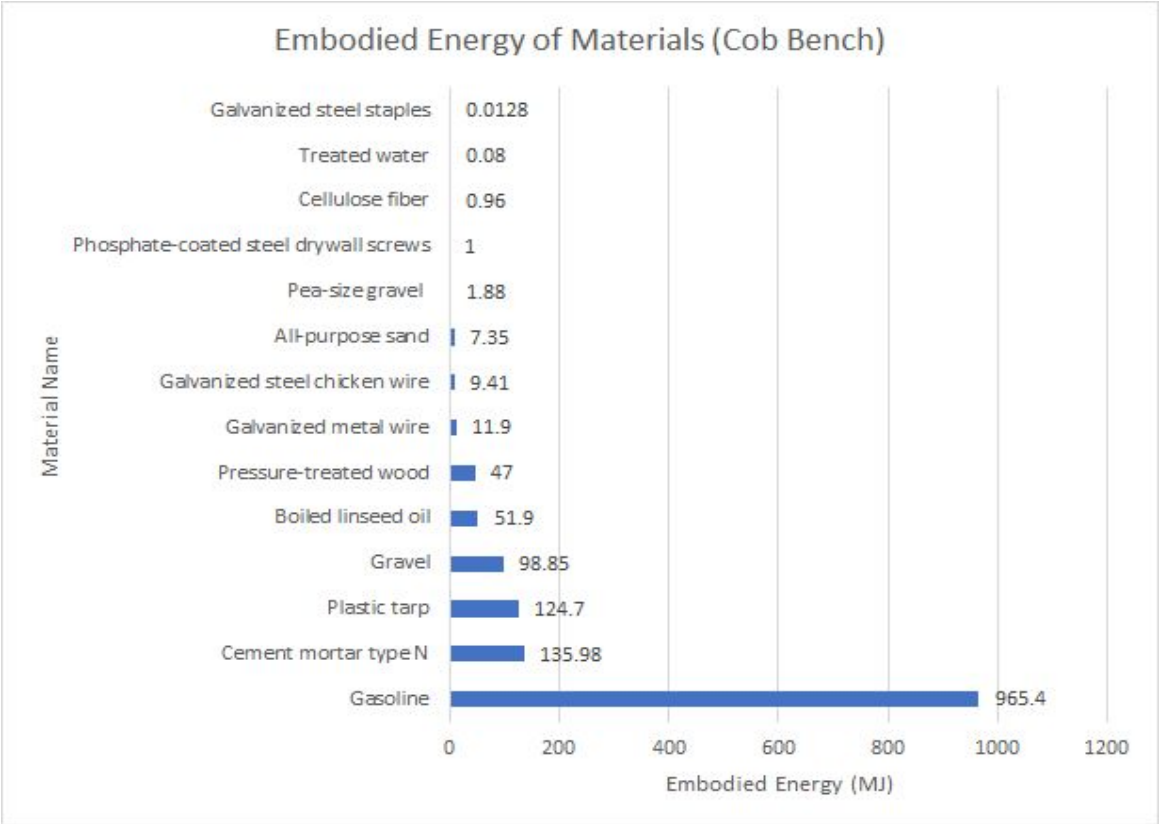


Figure 28. The embodied energy of materials in the cob bench.

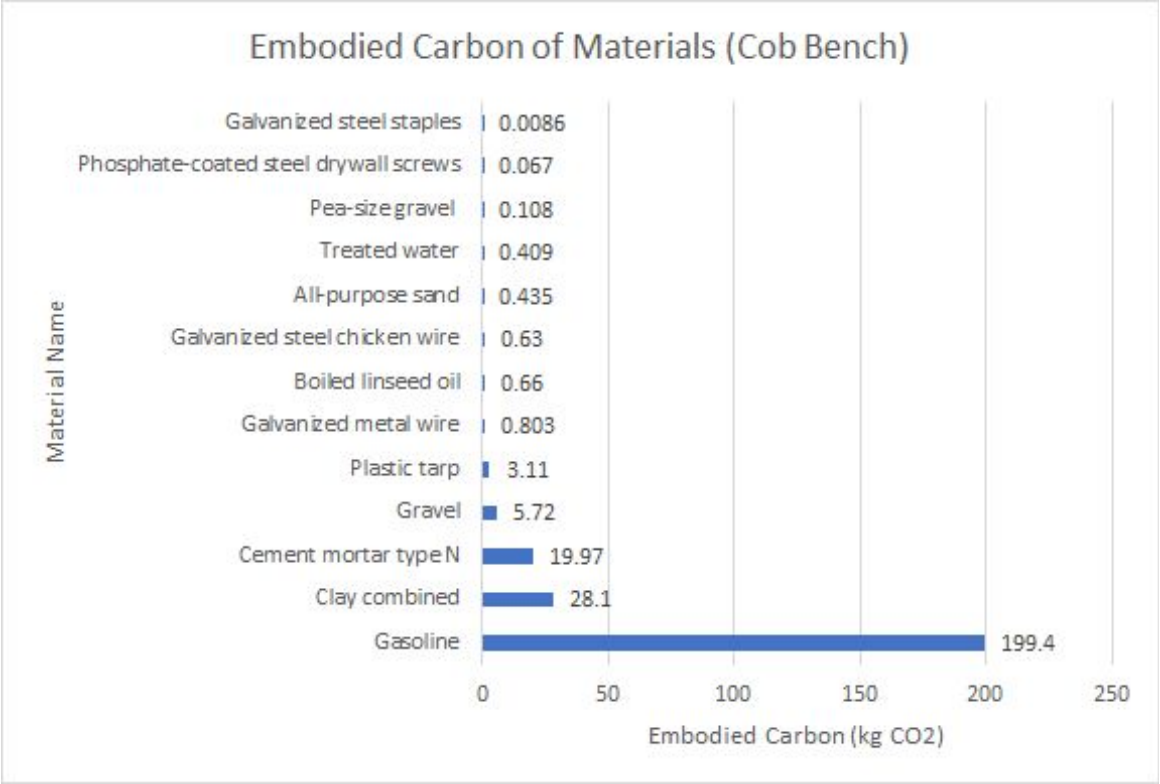


Figure 29. The embodied carbon of materials used in the cob bench.

Innova Aluminium Bench Results

Innova's aluminum bench costed $442.27, had an embodied energy value of 3884.3MJ, and had an embodied carbon value of 226.2kg CO_2, as seen in table 4 below. The aluminium contributed the most in terms of embodied energy and embodied carbon. Its embodied energy was 3291.3MJ, 3042.96 more megajoules than the next highest embodied energy material, the concrete. Aluminium's embodied carbon was also 142.2kg higher than the concrete. The aluminum bench's stainless steel hex nuts contributed the least to both embodied energy and embodied carbon with 3.08MJ and 0.092kg CO^2, respectively.

Table 4 - LCA for Innova Aluminium Bench

Material*	**Weight (kg)**	**Embodied energy (EE) MJ[a]**	**Embodied Carbon (EC) kg CO_2[a]**	**Cost USD**
Aluminium	20.7kg	3291.3MJ	171.4kg CO_2	N/A
Stainless steel 5/16in hex nuts	0.0544kg	3.08MJ	0.092kg CO_2	N/A
Stainless steel 5/16in x 1in bolts	0.172kg	9.75MJ	0.288kg CO_2	N/A
Concrete	275.78kg	215.1MJ	29.2kg CO_2	$31.54
Gravel	308.4kg	25.6MJ	1.48kg CO_2	$21.73
Heavy fuel oil	N/A	91.15MJ	6.56kg CO_2e	N/A
Diesel	N/A	248.34MJ	17.15kg CO_2e	N/A
Total	**N/A**	**3884.3MJ**	**226.2kg CO_2**	**$442.27[b] (not assembled)**

*****Innova Metro 51 in. Cast Aluminum Bench [L 51in x W 24.3in x H 33in, 21kg] (Innova, 2016).
[a]Values come from (Jones, 2011).
[b]Retail price of the bench was $389 (Innova, 2016).

Aluminum counted for nearly 85% of the bench's total embodied energy value, as well as roughly 76% of its total embodied carbon. The next highest material value for

embodied carbon was concrete at 29.2kg CO_2, only contributing 13% to the total embodied carbon value. These values are expressed in *Figure 30,* embodied energy and *Figure 31,* embodied carbon below.

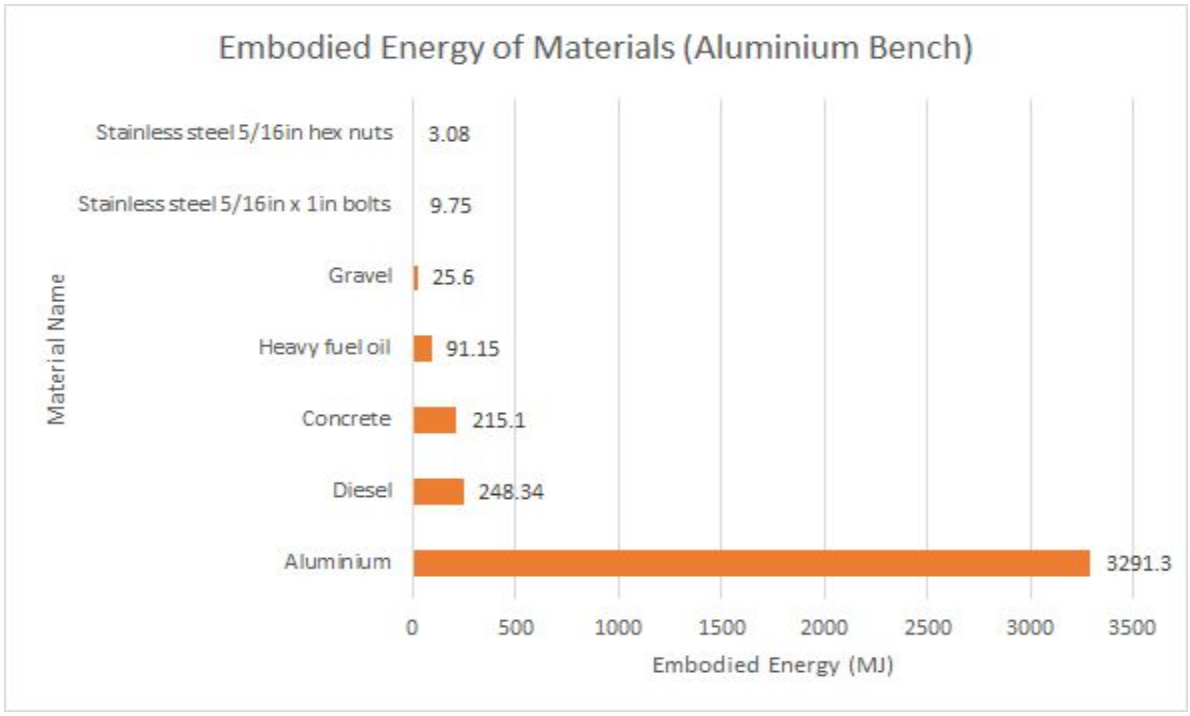


Figure 30. A graph which explains the embodied energy of materials used in the Innova aluminium bench.

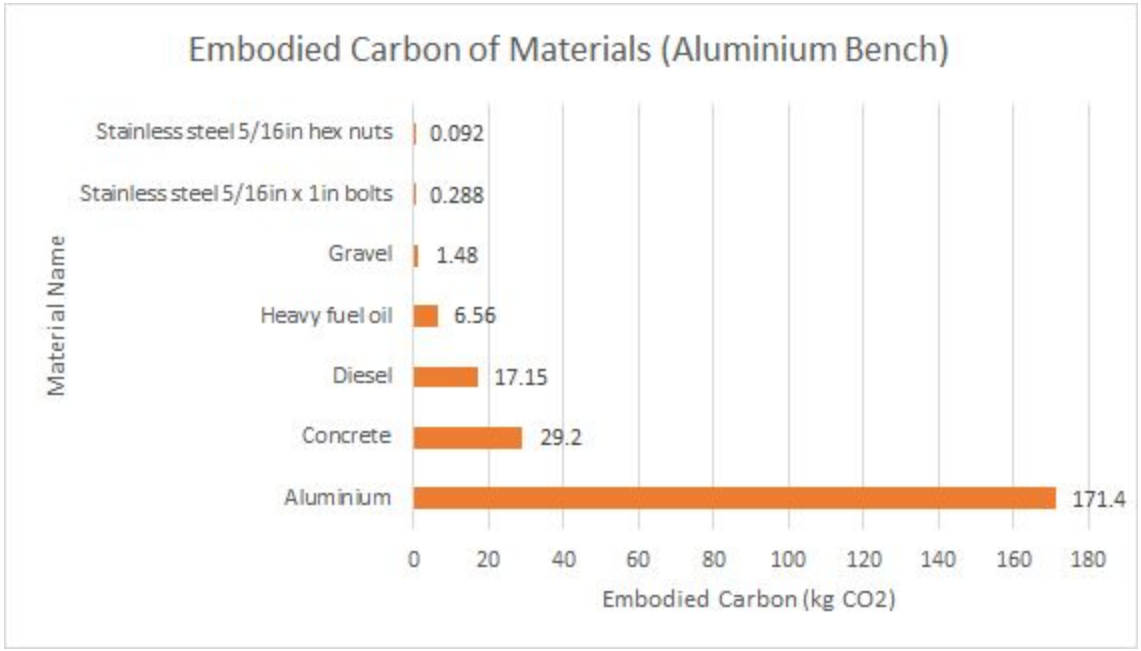


Figure 31. A graph depicting the embodied energy of materials used to build the Innova aluminium bench.

VIFAH Hardwood Bench Results

VIFAH's hardwood bench had an embodied energy value of 597.01MJ, an embodied carbon value of 51.2kg CO_2, and cost $229.54. This values are expressed in Table 5 below.

Table 5 - LCA for VIFAH Hardwood Bench

Material*	**Weight (kg)**	**Embodied energy (EE) MJ[a]**	**Embodied Carbon (EC) kg CO_2[a]**	**Cost USD**
Acacia hardwood	13.6kg	106.1MJ	1.74kg CO_2	N/A
Concrete	301.19kg	234.9MJ	31.9kg CO_2	$34.45
Gravel	326.59kg	27.1MJ	1.57kg CO_2	$19.60
Heavy fuel oil	N/A	68.05MJ	4.88kg CO_2e	N/A
Diesel	N/A	160.86MJ	11.11kg CO_2e	N/A
Total	**N/A**	**597.01MJ**	**51.2kg CO_2**	**$229.54[b] (not assembled)**

*****Vifah Hardwood Garden Bench [L 57in x W 24in x H 34in, 13.6kg] (Sears, 2016).
[a]Values come from (Jones, 2011).
[b]Retail price of the bench was $175.49 (Sears, 2016).

The material that had the highest EE and EC values was the concrete for the bench's foundation. It accounted for 62% of the total embodied carbon value, and 39% of the total embodied energy of the bench. The second highest was the diesel used in transportation, accounting for 27% of the total embodied energy value and 22% of the total embodied carbon. These values are compared in *Figure 32* (embodied energy) and *Figure 33* (embodied carbon) below.

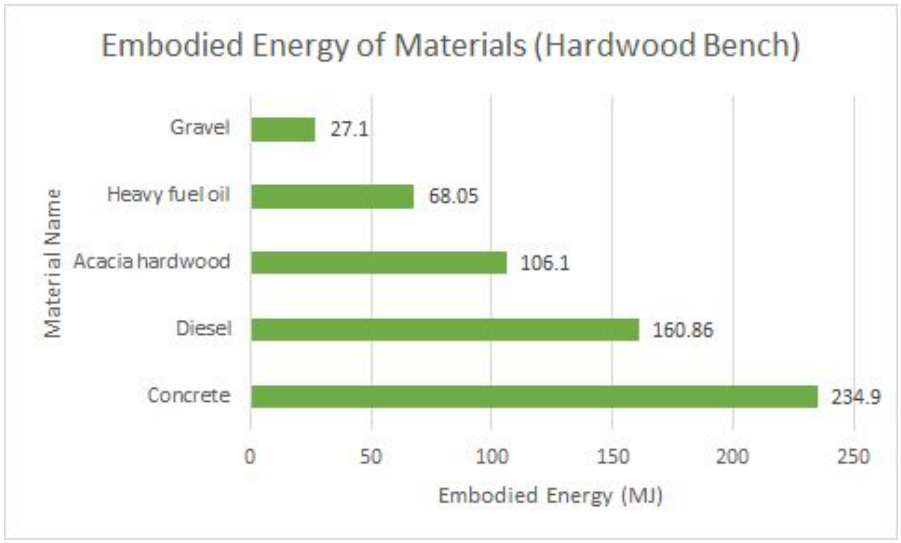


Figure 32. A graph detailing the embodied energy of the VIFAH hardwood bench.

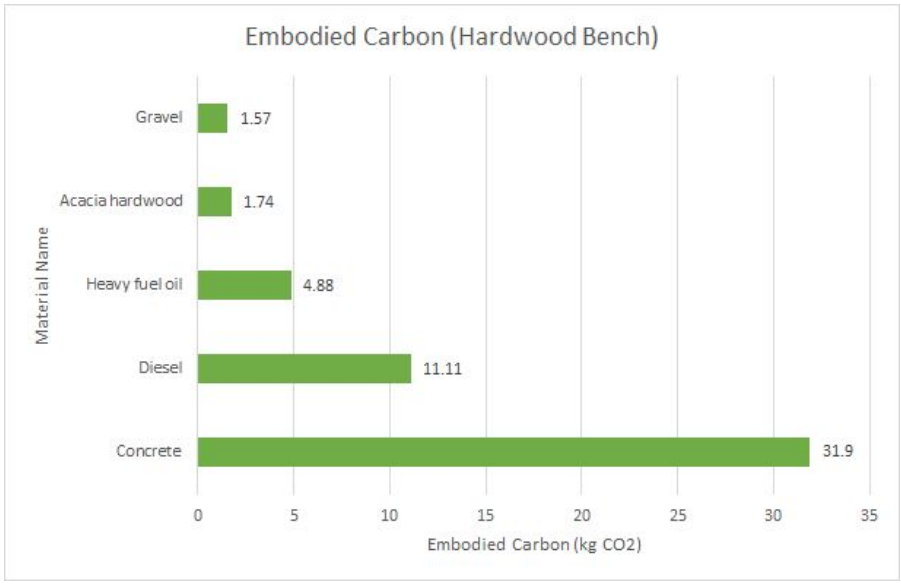


Figure 33. A bar graph depicting the embodied carbon of materials used in the VIFAH hardwood bench.

Bench Values Comparison

Figure 34 below depicts each of the benches and how they compare to the others in terms of all three criteria (EE, EC, and cost).

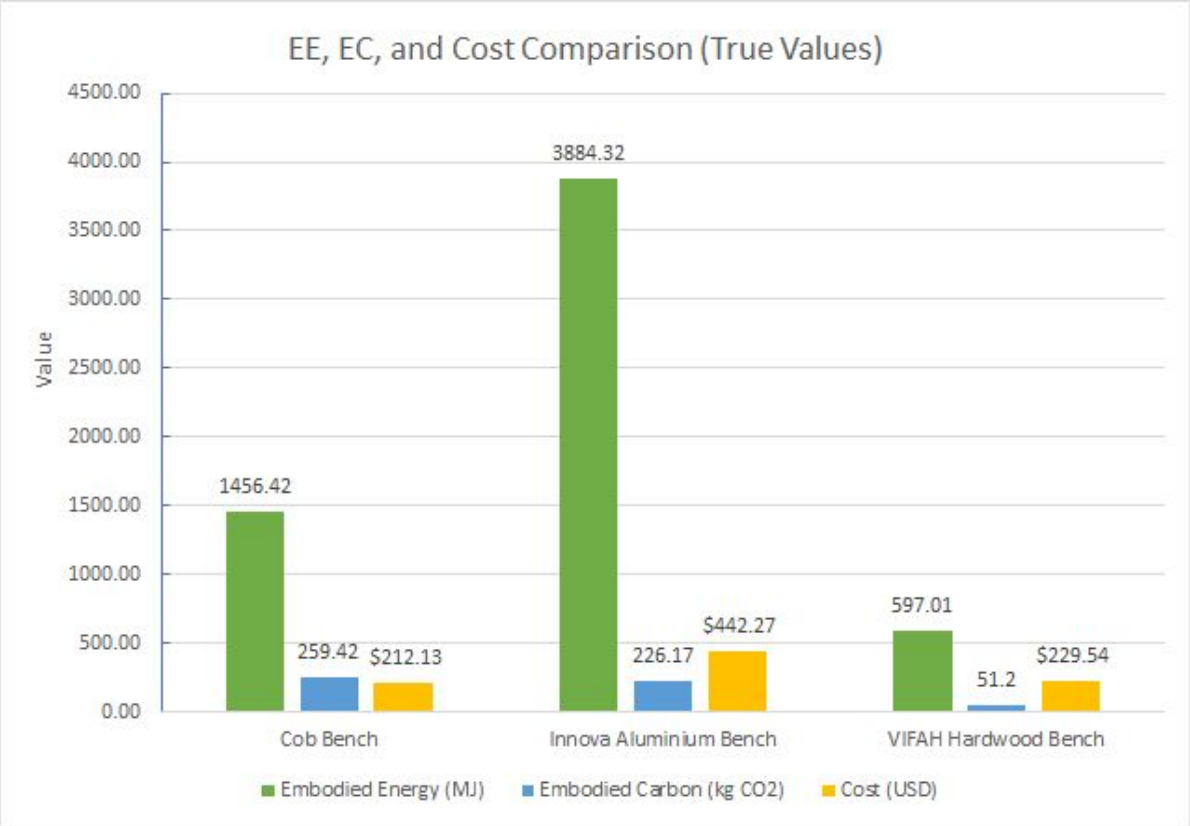


Figure 34. A chart comparing the embodied energy, embodied carbon, and cost values by each bench type. Green is embodied energy in MJ, blue is embodied carbon in kg CO_2, and yellow is cost in USD.

As is shown in the figure above, the cob bench had the highest embodied carbon value compared with the other two benches, but was also the most economical. It produced 33.27kg CO_2 more than the aluminium bench, and 208.22kg CO_2 more than the hardwood bench. The Innova aluminum bench had the highest embodied energy value by a large margin--it was over twice the embodied energy of the cob bench and 6.5 times that of the hardwood bench. The hardwood bench had the lowest embodied energy and embodied carbon values of all three benches, but was still more expensive than the cob bench. Its EC value was less than ¼ of that of the aluminium bench, and was roughly ⅛ of the amount of carbon produced by the cob bench.

Discussion:

Overview

Between the three benches, the cob bench had the highest value for embodied carbon, middle value for embodied energy, and was most economical in terms of cost. The aluminium bench from Innova was worst in regards to embodied energy and cost. VIFAH's hardwood bench was best for embodied energy as well as embodied carbon, and thus had the least environmental impact of all three benches.

Reasons Why The Cob Bench Had The Highest Embodied Carbon: Building Concessions and Inexperience

There are a number of reasons why the cob bench was not the most environmentally friendly bench compared with the others. The two most important contributing factors were high gasoline usage and my inexperience in cob-building.

Because of my inexperience in building, I used much more gasoline to make trips to and from Home Depot than if I had known all the various materials and quantities I needed before building. This will be explained more in depth in the next section. My inexperience also contributed to choosing certain materials that had relatively high impacts on the EE and EC values. An example of this is the cement mortar N. In many of the cob books, they suggest using lime mortar because it is more environmentally friendly, but also suggest using cement mortar if inexperienced (Weismann & Bryce, 2007; Evans, Smiley, & Smith, 2002). Lime mortar is more environmentally friendly because it absorbs the CO_2 it creates when mortaring the stones, but hydraulic lime can be very caustic and difficult to work with for beginners (Weismann & Bryce, 2007; Evans, Smiley, & Smith, 2002).

Another concession I had to make while building was using powdered clay. It is highly preferable for any cob project to use materials that occur naturally around the building site. In fact, one of the reasons I chose to do cob is because I heard farmers in the area say there was a lot of clay in the soil. Unfortunately, the jar tests I performed begged to differ. If I had been able to use the earth I excavated for my cob mix, it would

have eliminated the embodied energy and embodied carbon of the powdered clay that I used as digging from the earth would not use any fossil fuel-powered energy.

Reasons Why The Cob Bench Had The Highest Embodied Carbon: Gasoline

More than any other material in my cob bench, gasoline contributed the most in terms of both embodied energy and embodied carbon. It contributed over seven times as much embodied carbon as the next highest material, the combined clay values. There are three main reasons why my gasoline value was so high: inexperience, very hot weather, and the type of vehicle used.

Because I was using a 2012 Nissan Sentra sedan/compact car, many trips had to be made to transport very heavy materials so as to not damage the vehicle. This explains why I had to go to Robertson Field multiple times to move the heavy rocks in my car. Thankfully, Kerstin Martin was able to help me move at least a quarter of the rocks via a pickup truck. If I were driving a pickup truck for the whole duration of this project, I would have made fewer trips. Even with a worse fuel efficiency in the truck, it would still have used less gasoline overall. This is discussed in the next section.

In addition, I had to make multiple trips because I was mostly working alone. The stones, gravel, and dirt was very heavy and my site was in an area without shade. Though I mostly started early in the morning or in the late afternoon to avoid the hottest parts of the day, being in the sun and doing heavy manual labor such as mortaring large stones or shoveling dirt or gravel was very tiring and I worked for roughly 5 hours a day. If I had helpers, the work would have progressed faster, but most gasoline would have to have been accounted for.

Finally, my inexperience in any type of building caused me to make many trips to Home Depot. If I were to build another bench after learning all I have building this one, I hypothesize I could cut the amount of trips I went to Home Depot in half. For these reasons, I recalculated the LCA for my cob bench with new gasoline values.

Bench Comparison With Augmented Gasoline Values

For comparison, another calculation of the cob bench was performed with different transportation information, as gasoline contributed the most for both EE and EC values. This transportation information is theoretically based on if I was to make this bench with all of the information I had learned previous to building it.

The assumptions are as follows: instead of using a 2012 Nissan Sentra sedan, I would use a Ford F-150 light duty pickup truck and make fewer trips to Home Depot and Robertson Field and from Allegheny. Only 20 trips to and from Allegheny to the MARC would be made, as well as 6 trips to and from Home Depot. The total amount of miles travelled in the truck would be 65.1 miles. With the Ford's fuel economy of 18mpg in city, that means 3.61 gallons of gasoline would be used (EPA). Therefore, as a gallon of gas weighs 2.78kgs, 3.61 gallons equals 10kgs of gasoline.

With this new gasoline information, the cob bench would have the following values: embodied energy of 1414.63MJ, embodied carbon of 215.45kg CO_2, and would cost $202.52. Comparing the new values of the cob bench versus the other benches would look like *Figure 35* below.

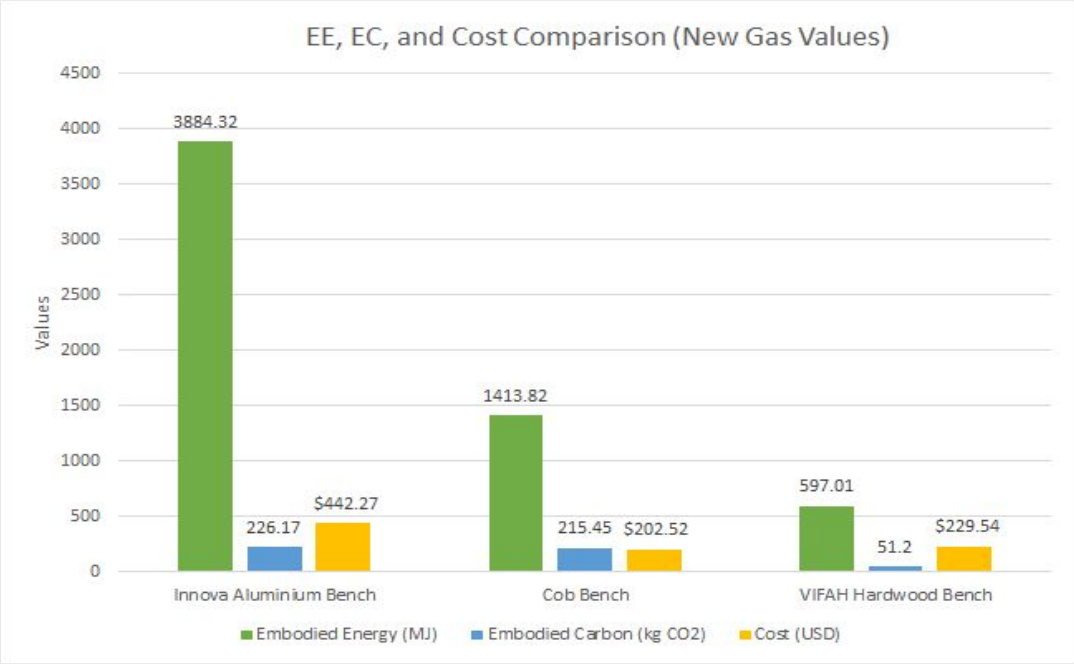


Figure 35. This chart compares all three of the benches, but now with the new gasoline values for the cob bench.

As seen in the figure above, the aluminum bench is now the least environmentally friendly in both categories of embodied energy and embodied carbon, as well as being the most expensive. The cob bench now resides in the middle of all three benches in terms of embodied energy and embodied carbon, but is still cheaper than both benches. The VIFAH hardwood bench still remains the least environmentally damaging option in terms of both EE and EC. It is important to note that even with augmented values, the cob bench will always produce more carbon than the hardwood bench because the most efficient gasoline value still an EC value of 152.3kg. The carbon produced from driving alone was three times higher than the entire embodied carbon value of VIFAH's hardwood bench.

Finally, the last situation is the best case scenario: working on a site which provides a good mix of both clay and sand, using lime mortar instead of cement mortar, using natural wood around the site, re-using someone else's plastic tarp so as to not incur the first time EE and EC values, and using the least amount of gasoline possible. Re-using any tool or material eliminates any EE or EC attached to it as those environmental impacts were attributed to the person who first purchased the tool or material.

Hydraulic lime mortar is one part cement, one part lime, and 6 parts sand with an EE value of 1.03MJ/kg and an EC value of 0.155kg CO_2e/kg (Jones, 2011). This value is not wholly accurate, as true lime mortar is simply lime and sand. It is assumed that the same weight of lime mortar would be used as cement mortar, 122.5kg. This also may not be accurate, but calculations were not able to be made for how much lime mortar would be needed. One bag of "cream" mortar, the 1:1:6 mix, is $8 for 20kg (Walkers Hardware). 6 and ⅛ bags are necessary. These new values are compared in *Figure 36* below.

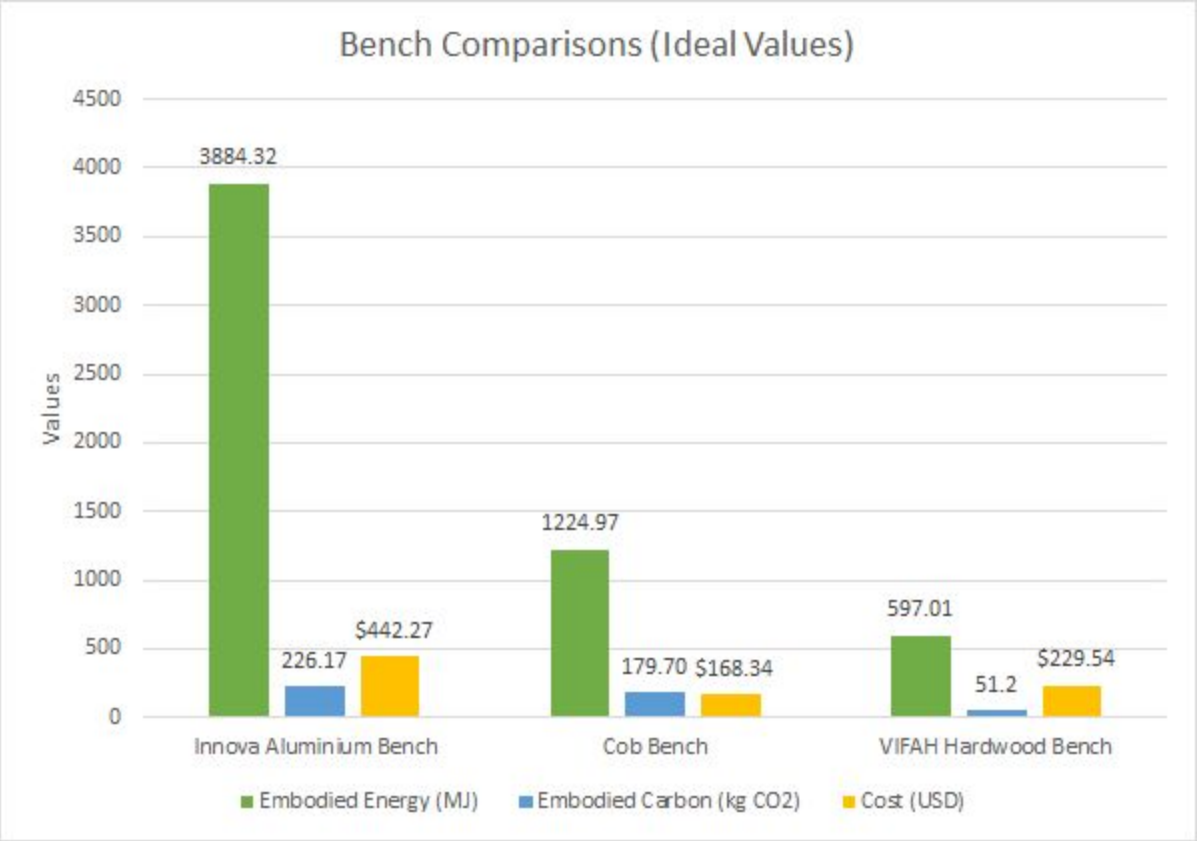


Figure 36. The three different benches with perfect scenario values for the cob bench.

As is shown in *Figure 36* above, the cob bench still remains in between the aluminum and hardwood benches in both embodied carbon and embodied energy. Even in this ideal situation, the cob bench would never have a lower embodied carbon or embodied energy value against the hardwood bench because gasoline's value alone accounted for 922.8MJ and 152.3kg CO_2. Both of these values are two to three times higher than the hardwood bench's total EE and EC values of 597.01MJ and 51.2kg CO_2, respectively.

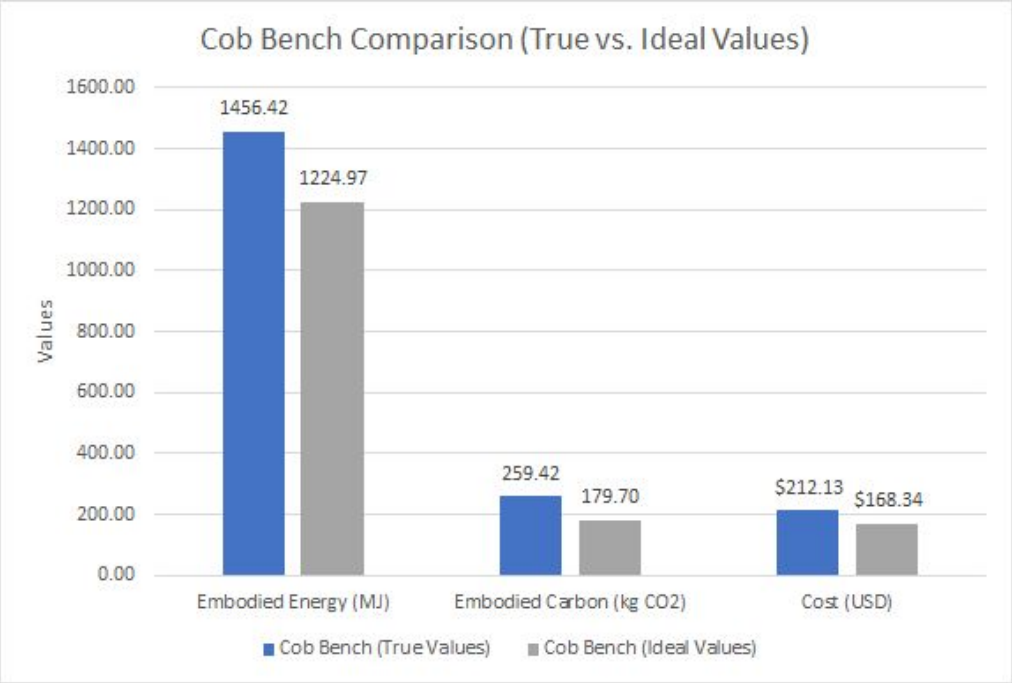


Figure 37. The cob benches with the true and ideal EE, EC, and cost values.

Shown in *Figure 37* above, the cob bench's embodied carbon value has decreased by 87.91kg from 259.42kg CO_2 to the ideal scenario's value of 171.51kg CO_2. The most drastic decrease happened in the embodied energy category--the ideal scenario lessened the embodied energy used by 231.43MJ. That being said, the lime mortar values used in the ideal situation don't take into account is that lime mortar sequesters carbon from the surrounding air as it begins to dry (Evans, Smiley, & Smith, 2002; GreenSpec, 2017; Lime Green Products Ltd). As hydrated lime sequesters 0.535kg per kg of hydrated lime used, 8.19kg of CO_2 will be eliminated over time (Schlegel & Shtiza, 2014). Because of this, it will be deducted from its embodied carbon value, which would decrease from 18.99 to 10.8kg CO_2. This calculation was excluded as the LCA conducted is cradle to site, not cradle to grave or later.

Study Limitations

There was also a number of limitations in this study. For example, the transportation information used for the aluminium and hardwood benches assumed they

were manufactured and shipped directly from their respective shipping ports. A more realistic scenario is that materials were manufactured further in country and then transported to the shipping ports. In addition, this study does not take into account the energy required in manufacturing each one of the benches. The values shown is simply for the EE and EC values of the materials themselves, not the manufacturing of the bench. Because of this, both bench's embodied energy and embodied carbon values are lower than they would be were both LCAs perfect.

In addition, many of the embodied energy and embodied carbon values used in both LCAs were derived from Jones 2011 study--specifically quantifying these values from processing within the UK. Because there can be different manufacturing processes per country, some of the values included in this study could be inaccurate for the United States. Finally, the values gathered from Carnegie Mellon's EIOLCA tool date from 2002--meaning it is very possible these values have changed in the 15 years in between those values and the writing of this study.

Alternative Benefits Of The Cob Bench Over Others

While this study found the cob bench was the least environmentally friendly bench in terms of embodied carbon, there are other benefits that it brings which the others do not. For example, this study does not take into account longevity of the benches. While the powder coated aluminium bench would most likely exist the longest, cob can stand for centuries if it was made and protected well. In addition, the cob bench I built is completely original--even if someone were to try and replicate it perfectly, it would not be the same bench as it would not be on the same property and be shaped or mixed the exactly same way. This is in direct contrast with the two other benches which are replicated and sold commercially at a large scale.

In addition, cob benches have the ability of being used as a community building projects. Where the two other benches could be easily assembled by one or two people, a cob bench is a multi-day endeavor which can involve multiple people dancing in mud on tarps and building something unique with their hands. While these features are not

easily measured, they set the cob bench apart. It also has the ability of being used as a teaching feature--letting people know that there are other building options out there versus the conventional styles that are always seen.

Finally, there is something to be said for the cob bench being the least expensive option. It costs only $212.13, which is less than half of that of the aluminum bench and $17.41 less than the hardwood bench. Combining the low dollar value of cob bench with the community building aspect, its possibility to be used as a learning component, and its originality, this makes the cob bench even more valuable than before.

Future Research and Final Thoughts

To condense the findings of this study into a single phrase, 'the devil is in the details'. While cob seems like a sustainable building style in theory, it can quickly become unsustainable when details change in practice. That being said, it also brings unique style and properties to the concept of building. It has been demonstrably cheaper than the other two benches in this study, and it is completely unique in design and aesthetic. With all of the various health, energy, community, and aesthetic benefits of cob, it should still be researched as an building option. Depending on what aspects a builder or community prioritizes, cob could still be the right option for them. This is especially so if new cob structures pay close attention to the pitfalls of the cob bench in this study--primarily the gasoline and powdered clay.

Many of these factors such as gasoline consumption could be reduced or eliminated altogether if the study were to be performed again. For example, being able to source clay and sand from the building site would greatly reduce trips for materials as well as eliminate the purchase of these materials. For this reason, further study should be proposed to conduct a Pennsylvania state soil test to determine the areas that are best suited for building cob. If this is successful and cob building begins to become more common, national soil testing should be performed. This would give an overview of where best to build cob in order to make it as environmentally sustainable as possible.

In addition, cob may perform better versus conventional building if done on a larger scale such as building houses. This could be so for a number of reasons. First, unlike the benches discussed in this study, houses cannot be transported. This would increase the transportation costs of all of the conventional houses whereas the cob house transportation would be less because the majority of materials are re-used or gathered from the site. As was shown in this study, transportation was a huge determining factor to the environmental impact of a cob project. Secondly, more materials would have to be manufactured and used in a conventional house versus a cob house. Provided whomever was building the cob house would be sourcing clay and sand manually from the site around them, they would continue to see environmental benefits versus the other house as shovelling clay and sand does not produce CO_2 emissions. In contrast, conventional house builders would have to continue to buy or manufacture materials. Even if these materials were green or sustainable, they would still use energy and emit GHGs.

Cob houses being more sustainable than conventionally built houses is already supported by the limited literature available. As highlighted in Estrada's 2013 study of a cob house LCA versus a house of comparable size made from concrete, the cob house created 8,340kg CO_2, whereas the concrete house created 18,525kg CO_2. That being said, this is the only LCA study on cob houses. There need to be more studies in order to get a fuller picture of how cob compares to other building styles. As there are already known cob houses built in Oregon, LCAs could be conducted on these houses versus a theoretical house built with conventional materials. These are the steps we need to take in order to move towards more sustainable lifestyles.

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