Exploring Embodied Carbon within Smith College Construction: Utilizing the New Neilson Library as a Case Study

Larissa Holland
Smith College

Rebecca Miller
Smith College

Lydia Sheyda
Smith College

Exploring Embodied Carbon within Smith College Construction

Utilizing the New Neilson Library as a Case Study

Larissa Holland, Rebecca Miller, Lydia Sheyda

Smith College Senior Capstone

Advised by Alex Barron and Dano Weisbord

ENV 312 | May 7, 2020

Executive summary

According to the Carbon Leadership Forum, the built environment contributes to almost 40% of CO2 emissions worldwide each year. While much of the greenhouse gas (GHG) emitted from structures is a result of the energy required to operate the lighting, heating, and cooling of existing buildings, it has been calculated that embodied carbon will be responsible for roughly half of the total new construction emissions between now and 2050. At an institutional scale, Smith College has made great progress in improving the energy and structural efficiency of building operations and expanding renewable energy initiatives. However, with construction being responsible for roughly 65% of the institution's Scope 3 GHG emissions, the next frontier of work is to identify, address, and reduce embodied carbon in buildings by lowering the emissions from material manufacturing and the construction processes. By using the open-access Embodied Carbon in Construction Calculator (EC3) developed by the Carbon Leadership Forum, as well as utilizing the Life Cycle Assessment completed by Thornton Tomasetti, this project calculated an estimate of the emissions associated with the foundational concrete and structural steel used in the construction of Neilson Library. This project has three main products: 1) A detailed identification of two major carbon hotspots and their connection to Smith's Scope 3 GHG emissions; 2) The calculated embodied carbon associated with two of the most prevalent materials used in the construction of Neilson Library; 3) A brief analysis of potential alternative materials as well as recommendations that could be used to lower the embodied carbon within new construction. By addressing embodied carbon within the capitol construction sector, Smith could both rise as a leader among Higher Education Institutions (HEIs) and make steps towards developing a reduction plan for their Scope-3 GHG emissions.

Introduction

With the continued growth of urban centers and the expansion of the built environment, it has been calculated that 6.13 billion square meters of buildings are constructed worldwide each year (Architecture 2030). For climate specialists, this is an incredibly alarming statistic due to the sense of urgency regarding the climate impact of constructing buildings. In the United States alone, residential and commercial buildings account for 40% of all energy consumption (U.S. Energy Information Administration). Globally, buildings are responsible for 39% of carbon emissions (World Green Building Council). While many opportunities exist to mitigate greenhouse gas (GHG) emissions in the built environment and construction sector, the approach that architects, engineers, and general construction consultants have taken up to this point is advocating for stronger energy efficiency standards and renewable energy production, which does a great job of addressing the operational side of carbon emissions (Pomponi & Moncaster 2016). However, it is becoming increasingly evident that addressing embodied carbon, which is the total sum of GHG emitted in the manufacturing, production, transportation, incorporation, recycling, and disposal of all building materials used during the creation of new buildings, is crucial in order to truly decarbonize the construction sector.

Unlike operational carbon, which can be addressed over time by expanding green energy initiatives and advancing structural efficiency, embodied carbon is set in place once a building is constructed. Accounting for all new construction from now until 2050, embodied carbon emissions will be roughly equivalent to operational carbon emissions (Fig. 1). As the pressures and complexities of GHG emissions continue to grow, HEIs are beginning to see their role in reducing contributions to global warming on an operational level. Smith College is a leader in collegiate sustainability, supporting a range of initiatives focused on countering and mitigating the effects of climate change both inside and outside of the classroom. While Smith has taken many innovative and progressive steps to reduce the carbon footprint of the college, such as participating in the first-ever collaborative purchase of New-England generated solar electricity by a high education consortium, perhaps the most notable step is the college's commitment to being climate-neutral by 2030 (Sustainable Smith). In an effort to reach this ambitious goal, Smith has developed reduction plans for both the institution's Scope 1 greenhouse gas (GHG) emissions and the Scope 2 GHG emissions. However, the College has not yet developed a reduction plan for its Scope 3 GHG emissions due to much of the data being hidden and therefore difficult to calculate.

Thanks to the work of former ENV 312 students, we know that one of the largest components of Smith's Scope 3 emissions is construction, which is responsible for 65% (Fig. 2) (Cara Dietz 2018). While operational reduction continues to be flagged by entities such as Smith's Study Group on Climate Change, the Sustainability and Climate Action Management Plan, and the Committee on Sustainability, the area that is not being highlighted as aggressively is embodied carbon in the built environment. In the coming years, while Smith's operational carbon will continue to be reduced, the amount of embodied carbon will continue to grow in importance as a proportion of the college's complete emissions. In order to understand where the greatest opportunities for mitigation and reduction might lie within Capitol Construction, this project aims to analyze useful data that could lead to construction policies being adopted regarding an embodied carbon awareness plan, influence the College's behavior, and drastically change the amount of carbon existing within the construction supply chain.

Methods

"The embodied energy research field is plagued with methodological issues. There is no scientifically agreed upon standard for calculating embodied energy, and uncertainty and

controversy surround the data collection process." - Patricia Frey, Director of Sustainability at the National Trust for Historic Preservation

Background Research

We started by conducting a detailed literature search of organizations and institutions doing work that either directly addressed the construction portion of Scope-3 GHG emissions in HEIs or worked to identify and reduce embodied carbon hotspots. So far, little research has been done on how HEIs specifically are considering embodied carbon within new construction, as well as renovation, and its impacts on their institutional carbon footprint. However, we learned through our research of many organizations and tools that are working and being used to rapidly transform the built environment away from being a major contributor of greenhouse gas emissions. These organizations and tools included: Architecture 2030, The Carbon Leadership Forum, The Embodied Carbon in Construction Calculator, The Inventory of Carbon and Energy, The World Green Building Council, and The Quartz Project. To better inform our project specifically, we reached out to Alexandra Davis and Amanda Garvey from Thornton Tomasetti, the consulting group that worked on the Neilson Library construction. Additional phone, email, and in-person conversations with Smith's Capitol Construction director Peter Gagnon and the director of Campus Planning Dano Weisbord helped us solidify our own project design process: calculating the embodied carbon associated with the concrete and steel used in the construction of the new Neilson, creating a cradle-to-grave infographic for the manufacturing of the library, and compiling a short list of researched alternative materials for concrete and steel that has considerably less embodied carbon.

Data Procurement and Processing

Our research suggested that while there are a number of different sources that may be used for embodied carbon data, the data normally originates from a Life Cycle Assessment (LCA). An

LCA driven by the EC3 tool, which is closely related to the cradle to grave analysis model, allowed us to present data on the approximate carbon embodied within certain Neilson construction materials (Monahan, J., & Powell, J. C., 2011). In order to appropriately ground our project in the case study of Smith College's newly constructed Neilson Library, our research relied heavily on data and resources provided by the Thornton Tomasetti consulting group. From their documents, which included an LCA of the new library, we identified concrete and steel as the materials that had the largest associated embodied carbon. We then started our analysis using the cradle to grave model: analyzing raw material extraction - the "cradle" stage - to cover the whole life cycle, including new materials added during the operation phase refurbishment and taking into account end of life processes - the "grave" stage (Melton, P. 2018).

The data provided by the Thornton Tomasetti consulting firm was delivered to us in the form of an excel spreadsheet. This included information regarding the volume, type, and recycled content of every material used in the basic structure of the library. However, the spreadsheet did not provide information regarding the source and/or manufacturer of each material. Therefore, we were unable to identify an exact number of $kgCO^2$ emitted into the atmosphere for the amount of carbon embodied within our two focus areas: foundational concrete and structural steel.

Concrete and Steel Embodied Carbon

Concrete is the most widely used artificial building material globally and its use has only increased in recent decades (Architecture 2030). However, concrete is carbon-intensive and responsible for 8% of global carbon emissions- if concrete were a country, it would have the third-highest emissions, surpassed only by the U.S. and China (Warburton 2019). Concrete consists of four main ingredients: cement, coarse aggregate, fine aggregate (usually sand), and water. Various admixtures and supplementary cementitious materials (SCMs) are used in some concrete mixes to improve the quality or manageability of the concrete or alter the setting time. The majority of concrete's carbon emissions stem from portland cement, the primary cementing material used. The production of portland cement accounts for an estimated 5% of global carbon emissions and depending on the mix ratio can account for over 90% of the associated embodied carbon of a concrete mix (Boarder et. al. 2016; Melton 2018). In a common cement mix (rated M20), portland cement makes up 15.8% of the mixture by weight but accounts for 90.9% of the embodied carbon associated with the cement (Fig. 3).

The simplest way to reduce the embodied carbon of concrete is to reduce the amount of portland cement included in the mix. Fly ash and slag cement are SCMs commonly included in concrete mixtures, and both are byproducts of other production processes; fly ash is a byproduct of electrical generation while slag is produced during iron production. Replacing a portion of portland cement with fly ash and/or slag cement can, therefore, be a convenient method for reducing embodied carbon. However, portland cement cannot be completely replaced as each ingredient has a different impact on the concrete's properties. Fly ash usually can replace 20-30% of portland cement in a mixture while slag cement which is more closely related to portland cement from a chemical standpoint can normally replace up to 50% (*Slag Cement Association*).

Steel has high embodied carbon due primarily to the energy-intensive extraction methods and the high temperature thus high energy requirement of production. The production of steel is responsible for approximately 6.6% of global carbon emissions (Melton 2018). In order to turn iron ore into steel, the ore must be refined. This is done either in basic oxygen furnaces (BOFs) or electric arc furnaces (EAFs). BOFs burn coke to extract iron ore and thus release a great deal of carbon dioxide into the atmosphere; EAFs, on the other hand, utilize electricity instead and can, therefore, have much lower carbon emissions (Shapiro 2020). U.S. industries mostly use EAF technology, and when examining steel embodied carbon this is an important distinction to make.

Steel can be recycled almost indefinitely, however. According to the American Institute of Steel Construction, 98% of structural steel and 81% of all steel products are recycled. In order to reduce embodied carbon in steel, there are few options: Ensuring EAFs are used and increasing the proportion of recycled steel are the primary ways to reduce embodied carbon. Reuse of structural steel has been proposed as a better alternative to recycling, but is not commonly used due to technical, logistical, and cost barriers (SteelConstruction.info). The best way to reduce embodied carbon associated with steel is to reduce the amount of steel used.

The Embodied Carbon in Construction Calculator

While a number of building-specific embodied carbon calculators are available to assist with carbon calculations during the building design stage, we chose to work with the free, cloud-based, open-access Embodied Carbon in Construction Calculator (EC3) tool to try and simplify the complexities of embodied carbon calculation. The EC3 tool allowed us to use the data from the Thornton Tomassetti consulting firm to identify a range of $kgCO^2$ that could have been emitted during the manufacturing of the foundational concrete and structural steel of the New Neilson Library. This is displayed in the form of a boxplot with a range of likely emissions ranging from achievable (least carbon-intensive) to conservative (most carbon-intensive), an example of which can be found in the “Tables and Figures” section below (Fig. 4). All calculations, and their subsequent results, completed for this project within the EC3 tool are specific to the New England region.

Results

Foundational Concrete

For the 20% fly ash and 30% slag concrete mix used in the New Neilson foundation, the EC3 tool calculated the emissions per cubic yard to be between 187 $kgCO^2$ and 412 $kgCO^2$ (Fig. 5). The volume of concrete used to construct the New Neilson Library's foundation was 89,435 ft^3. Therefore, the total volume of concrete in the New Neilson has between 619,422 $kgCO^2$ of embodied carbon and 1,364,717 $kgCO^2$ of embodied carbon associated with it (Table 1).

Structural Steel

Based on data from the Thornton Tomassetti consulting firm, the total volume of structural steel within the New Neilson Library is around 34.65 ft^3. Despite having a comparable amount of information regarding the makeup of the steel beams, the EC3 tool would not respond to the input of structural steel data. Therefore, the range of $kgCO^2$ emitted by the manufacturing of the steel in the New Neilson Library is still unknown (Table 1).

Discussion

Main findings

Although our results did not yield specific measurements, the wide range of possible embodied carbon levels within concrete sources in the New England region shows the importance of sourcing. The conservative measurement was roughly double that of the achievable estimate. Therefore, ensuring a building has low embodied carbon is heavily reliant on thoughtful sourcing of materials. Additionally, this data is reflective of the 20% ash 30% slag concrete mixture that the Thornton Tomassetti consulting firm used based on its ability to reduce the overall embodied carbon without sacrificing strength (Purnell, P., & Black, L., 2012). This provides evidence for the complexity that accompanies embodied carbon calculations and the importance of sourcing from a low carbon emissions supplier.

The EC3 tool also conducts calculations for embodied carbon based on manufacturers. Additionally, the EC3 tool provides the list of manufacturers alongside the boxplot whose data they use to create the range. Because of this, one is able to sort through manufacturers and specifically select a source that is based on embodied carbon. This shows the impact of buying material with a solid knowledge base. If Smith wants to significantly reduce the amount of carbon embodied within buildings, the capitol construction team should review sourcing options independently from general contractors or find a contractor willing to conduct thorough research into the carbon embodied within various suppliers.

Alternatives

With each passing year, there are more innovative low embodied carbon products and solutions that are entering the construction market, and as technology and research continue to advance, these alternatives are going to become more diverse and more accessible. Portland limestone cement (PLC) is an alternative to regular portland cement that is lower in embodied carbon. Increasing the limestone content in portland cement to 15% results in a reduction of 12% of cement embodied carbon, and PLC requires about 10% less primary materials than portland cement, further reducing the environmental impact (Tennis et. al. 2011; Goguen 2014). Using PLC does impact the function of SCMs, however, and this must be taken into account when determining what portland cement alternatives to include.

Recycled aggregate concrete (RAC) replaces some or all of the coarse aggregate in a concrete mix with recycled concrete aggregate (RCA). While the impact of utilizing RAC on embodied carbon depends primarily on the distance from the recycling plant to the site, RCA use does reduce concrete end of life impacts and should be considered when identifying environmentally friendly concrete mixtures (Xiao et. al. 2018).

Carbon injected concrete such as that produced by CarbonCure is another alternative concrete that utilizes concrete for carbon sequestration. While we were unable to research this product more fully, it is something that should be looked into in future investigations.

Mass timber construction (MTC) is a relatively new alternative to traditional concrete and steel construction that can be significantly lower in embodied carbon. MTC comes in several different forms, including cross-laminated timber, Glu-Lam, and laminated veneer. The materials used in MTC are lower in embodied carbon and as MTC is primarily wood, it can even be considered as a form of carbon sequestration (Schnepf 2020). Additionally, the use of mass timber in buildings reduces the amount of concrete required in the foundation due to the lightweight nature of the material, further reducing embodied carbon (Zeitz et. al. 2019). There are some drawbacks to MTC, however. According to Alexandra Davis at Thornton Tomasetti, mass timber is a relatively new material to contractors and thus challenging to use. Furthermore, there are few sources for high strength mass timber in the United States which not only makes acquiring materials more difficult but also increases necessary transportation, causing the overall transportation impact to be larger than that for concrete or steel. Finally, while sustainably sourced mass timber can be environmentally beneficial, the use of illegal logging can negate any benefits and sources must therefore be carefully monitored. MTC has many benefits and many of the drawbacks are primarily due to MTC being a relatively new material and method; thus we can expect many of these drawbacks to decrease over time. For future projects, mass timber should be considered as an alternative to concrete and steel construction.

Environmental Product Declarations

An Environmental Product Declaration, or EPD, is an international certified report on the environmental impacts of a product over its life cycle. In order for a product to become EPD certified, an LCA for the product must be conducted, the data and other relevant information compiled into the EPD format and the report verified by an approved independent party. The primary benefit of EPDs is the transparent, verified, and comparable information available on an international standard, making it easy to examine life cycle impacts for a variety of products. EPDs are becoming increasingly popular and can be used to earn LEED certification points by demonstrating impact reduction compared to industry standards (The International EPD System). While we did not utilize EPDs in our examination of Neilson's embodied carbon, they are a valuable resource and future explorations into embodied carbon in construction should consider the use of EDPs for this purpose.

Limitations

Since embodied carbon is still a relatively new concept being taken into consideration around the world, we had few resources that could assist us in the completion of our analysis. The EC3 calculator was by far the most highly recommended tool we found; however, it is still in a Beta version. This led to a variety of bugs that impacted our research. The most detrimental being the tool's inability to provide data for structural steel. At the point we discovered this, it was too late to seek out another method of calculation and therefore left our exploration of structural steel incomplete.

Additionally, this report, a fair portion of the research, and the presentation of this work to stakeholders were completed during the COVID-19 pandemic. Mid-semester we found ourselves being forced to move from our on-campus housing and social distance all while completing our courses for the semester and our undergraduate careers. This was an enormous stressor and placed an astronomically large limitation on the amount of work we could complete on this topic.

Peer Institutions

Three HEIs that we thought were doing notable work related to embodied carbon are Emory University, the University of Washington at Seattle, and the University of New Hampshire. We did not compare or contrast any embodied carbon calculations amongst Smith and the highlighted institutions, partially due to the size of the three institutions being significantly larger than Smith. We also found with the scope of our project that it was most useful to observe and record what other HEIs are doing to address embodied carbon, rather than comparing Smith to them.

According to Emory University's Climate Action Plan, they have partnered with the consulting group “TruCost” in an effort to explore the amount of carbon embodied within their supply chain. As of 2017, the University of Washington at Seattle had a group of professors and students who were interested in researching embodied carbon and conducting LCAs for construction on campus. The University of Washington is also home to the Carbon Leadership Forum, a resource that we regularly used throughout our project (Peter Kelley 2017). Thirdly, in 2016, the University of New Hampshire (UNH) hired a Buildings and Embodied Carbon Fellow whose job was to incorporate embodied carbon into the institution’s carbon footprint calculations. This position was designed with the idea that it would bring more awareness to the role that embodied carbon played in UNH’s Scope-3 GHG emissions and could lead to a higher sense of urgency needed to mitigate those emissions (Brendan Hellebusch 2016).

Recommendations

After concluding our report and evaluating the outcomes and limitations highlighted above, we have created a short list of recommendations for Smith College Campus Planning, Smith College Capital Construction, and future student engagement.

To Smith College Campus Planning:

1. Explore the idea of independently reviewing the sources of materials for embodied carbon using either an open-source calculator or through a consulting group.
2. Set goals for embodied carbon within construction materials to meet "achievable" standards.

To Smith College Capital Construction:

1. Partner with contractors and consultants who make the reduction of embodied carbon within construction projects a priority.
2. Explore the idea of using mass timber in future projects.

To Future Students:

1. It would be really great to analyze how different embodied carbon calculators fare in comparison to each other. Some are spreadsheet-based, some use Building Information Modeling. It would make for a very interesting and important project to compare and contrast these calculators with Smith's needs in mind.
2. It would be helpful to know exactly how much of Smith's Scope 3 construction emissions are from embodied carbon in building materials.
3. Consider examining the EPD database for information regarding relevant construction products.

Tables and Figures

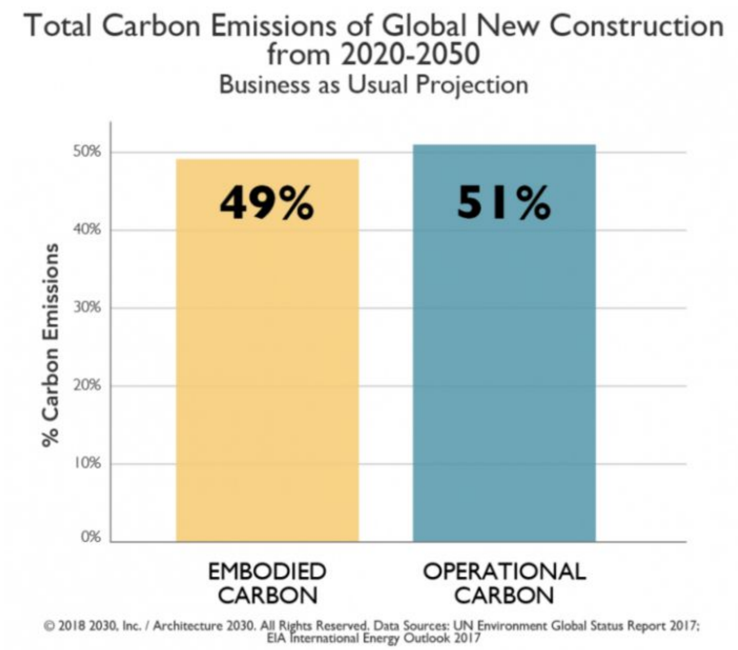

Figure 1: Comparison of embodied and operational carbon contributions as percentages of total carbon emissions from global new construction from 2020-2050.

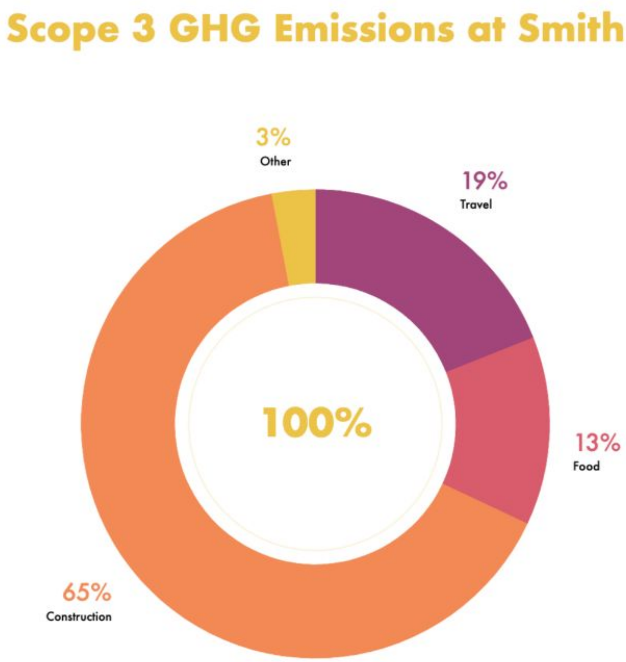

Figure 2: Scope 3 greenhouse gas emissions for Smith College broken down by sector

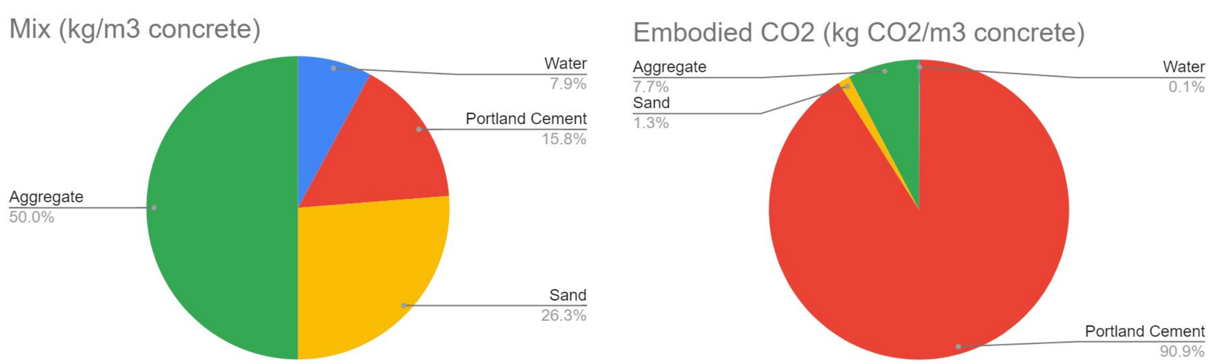

Figure 3: M20 concrete mixture comparing material weight and associated embodied carbon by material. Left: Constituent percentage of concrete mix by weight (kg/m^3 concrete) Right: Percentage of associated embodied carbon (kg CO_2/m^3) by constituent.

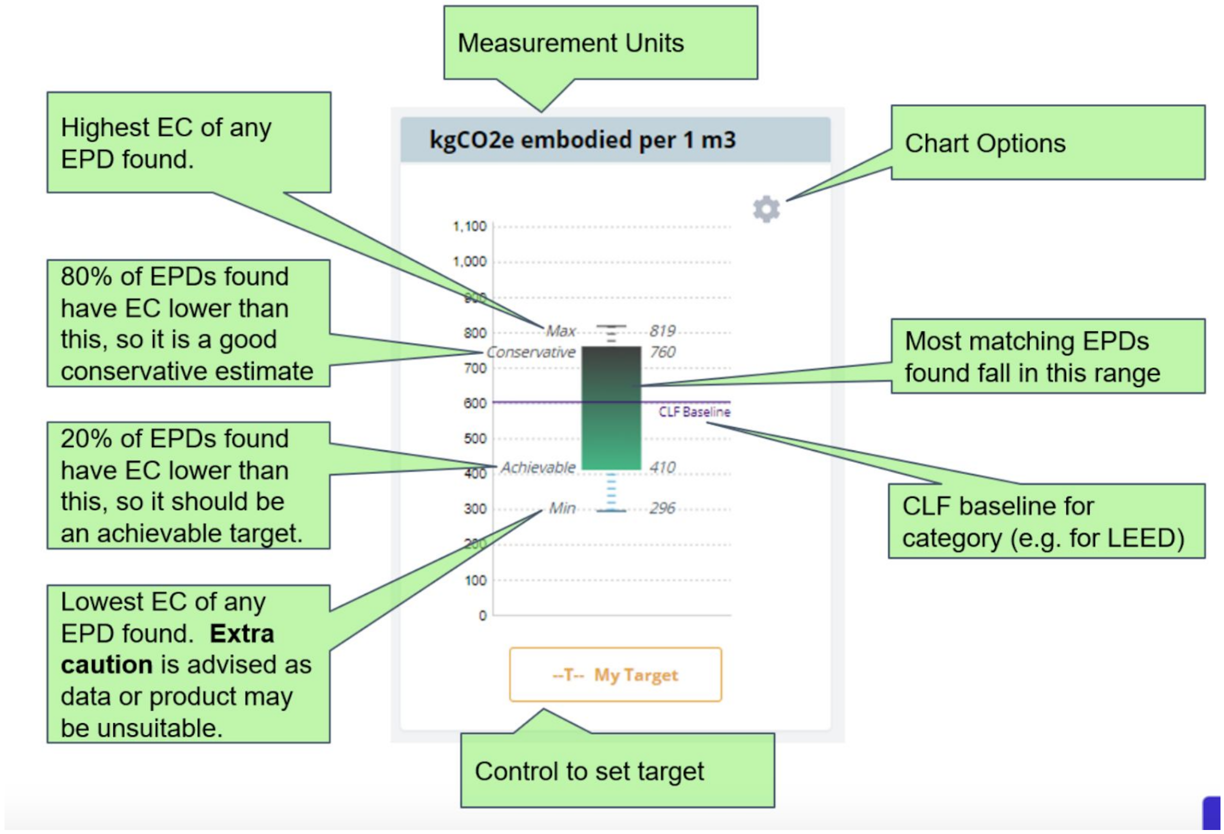

Figure 4: An Example of how the EC3 tool Presents Data on Carbon Emissions per Unit of Volume of Material.

Table 1: kgCO2 Emitted per Total Material in New Neilson Construction

	Volume (ft^3)	**Achievable ($kgCO_2e$)**	**Conservative ($kgCO_2e$)**
Foundational Concrete	89,435	619,422	1,364,717
Structural Steel	34.65	N/A	N/A

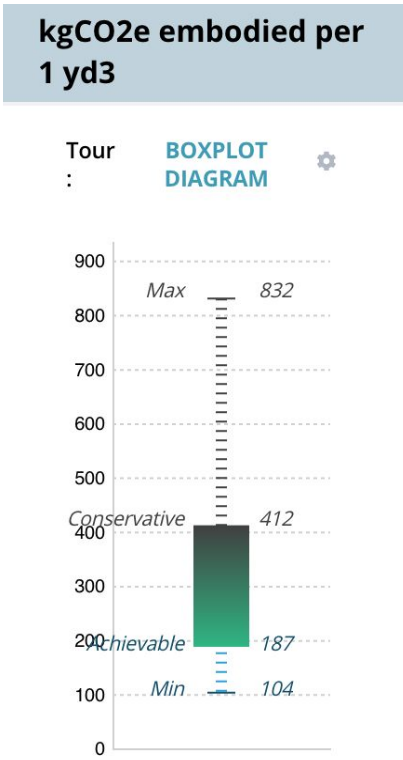

Figure 5: Achievable-Conservative Range of kgCO2 Emitted per Cubic Yard of Foundational Concrete in New Neilson.

Literature cited

1. *Architecture 2030*: Concrete - Carbon Smart Materials Palette. Retrieved from: https://materialspalette.org/concrete/.
2. *Architecture 2030:* New Buildings - Embodied Carbon. Retrieved from: https://architecture2030.org/new-buildings-embodied/
3. Boarder, R. F. W., et al. (2016). *10 - The Sustainability of Lightweight Aggregates Manufactured from Clay Wastes for Reducing the Carbon Footprint of Structural and Foundation Concrete.* Sustainability of Construction Materials (Second Edition), edited by Jamal M. Khatib. Woodhead Publishing: *ScienceDirect*.
4. *Carbon Leadership Forum*. Retrieved from: http://www.carbonleadershipforum.org/.
5. Circular Ecology. (2020). *Embodied Carbon Assessment.* Retrieved from: http://www.circularecology.com/embodied-carbon.html.

6. Dietz, C, Gevelber, E, Li, G. (2018). *Estimation of Smith College's Scope 3 Emissions*: https://scholarworks.smith.edu/other_projects/36.
7. *Frequently Asked Questions—The International EPD® System*. (n.d.). The International EPD System. Retrieved from https://www.environdec.com/contact/FAQ/.
8. Goguen, C. (2014). *Portland-Limestone Cement—National Precast Concrete Association*. National Precast Concrete Association (NPCA). https://precast.org/2014/06/portland-limestone-cement/.
9. Hellebusch, B. (2016). *Redefining Our Carbon Footprint Calculations to Include Embodied Carbon.* University of New Hampshire Sustainability Institute: https://sustainableunh.unh.edu/blog/2016/07/redefining-our-carbon-footprint-calculations-include-embodied-carbon.
10. Kelly, P. (2017). *Toward greener construction: UW professor leads group setting benchmarks for carbon across life of buildings.* UW News: https://www.washington.edu/news/2017/04/20/toward-greener-construction-uw-professor-leads-group-setting-benchmarks-for-carbon-across-life-of-buildings/.
11. Melton, P. (2018). *The Urgency of Embodied Carbon and What You Can Do About It.* Building Green. https://www.buildinggreen.com/feature/urgency-embodied-carbon-and-what-you-can-do-about-it.
12. Monahan, J., & Powell, J. C. (2011). *An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a life cycle assessment framework.* Energy and Buildings, *43*(1), 179–188.
13. Pomponi, F., & Moncaster, A. (2016). Embodied Carbon Mitigation and Reduction in the Built Environment– What Does the Evidence Say?. *Journal of Environmental Management*, *181*, 687-700.
14. Purnell, P., & Black, L. (2012). Embodied Carbon Dioxide in Concrete: Variation with Common Mix Design Parameters. *Cement and Concrete Research*, *42*(6), 874-877.
15. *Recycling and reuse*. (n.d.). SteelConstruction.Info. Retrieved from: https://www.steelconstruction.info/Recycling_and_reuse.

16. Schnepf, C. (2020). Sequestering Carbon in Cross-Laminated Timber. *Agriculture Climate Network*. https://www.agclimate.net/2020/02/26/sequestering-carbon-in-cross-laminated-timber/.
17. Shapiro, G. F. (2020). Concrete, Steel, or Wood: Searching for Zero-Net-Carbon Structural Materials. Architect Magazine. https://www.architectmagazine.com/technology/concrete-steel-or-wood-searching-for-zero-net-carbon-structural-materials_o.
18. "Slag Cement with Fly Ash." *Slag Cement Association*, https://www.slagcement.org/aboutslagcement/is-11.aspx.
19. *Structural Steel Sustainability | American Institute of Steel Construction*. (2020). American Institute of Steel Construction. https://www.aisc.org/why-steel/sustainability/
20. Tennis, P. D., Thomas, M. D. A., & Weiss, W. J. (2011). *State-of-the-art report on use of limestone in cements at levels of up to 15%* (pp. 10–20) [Technical Report]. https://www.researchgate.net/publication/292600685_State-of-the-art_report_on_use_of_limestone_in_cements_at_levels_of_up_to_15.
21. *U.S. Energy Information Administration*. Retrieved from: https://www.eia.gov/tools/faqs/faq.php?id=86&t=1
22. Warburton, R. (2019). Global Warming Has A Concrete Problem When It Comes to CO2. EcoRI News. https://www.ecori.org/climate-change/2019/10/4/global-warming-has-a-co2ncrete-problem
23. World Green Building Councils (2019). Bringing Embodied Carbon Upfront: Coordinated Action for the Building and Construction Sector to Tackle Embodied Carbon. Retrieved from: https://www.buildup.eu/sites/default/files/content/worldgbc_bringing_embodied_carbon_upfront.pdf.
24. Xiao, J., Wang, C., Ding, T., & Akbarnezhad, A. (2018). A recycled aggregate concrete high-rise building: Structural performance and embodied carbon footprint. *Journal of Cleaner Production*, *199*, 868–881. https://doi.org/10.1016/j.jclepro.2018.07.210

25. Zeitz, A., Griffin, C. T., & Dusicka, P. (2019). Comparing the embodied carbon and energy of a mass timber structure system to typical steel and concrete alternatives for parking garages. *Energy and Buildings*, *199*, 126–133.

Contributions

This semester brought a tremendous amount of unanticipated challenges with very little time to plan and organize. Without the help, patience, and transparency of all group members, the success of this project would not have been possible. L.H., R.M., and L.S. designed and executed the project in whole. L.H. mediated most of the in-person and email conversations with stakeholders, as well as formatted and drafted many written assignments. R.M. individually built many of our tables and figures, condensed much of our data, and was our "hand calculator" when experiencing difficulties with our online tools. L.S. heavily researched the pros, cons, and tradeoffs of alternative materials as well as designed many of the interview questions we asked our stakeholders. In addition, L.S. is responsible for the success of our organizational frameworks that kept us on track. L.H., R.M., and L.S. each contributed to articulating and communicating the methods, discussion, and results of our project and are collectively responsible for writing this report.