ASSESSING ENVIRONMENTAL IMPACT OF THE BUILT ENVIRONMENT BY ADOPTING LIFE CYCLE DESIGN

USING SWANTON PACIFIC RANCH AS A CASE STUDY

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ABSTRACT

Assessing Environmental Impact of the Built Environment by Adopting Life Cycle Design Using Swanton Pacific Ranch as a Case Study

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To combat the carbon emissions contributed to the atmosphere by the built environment, it is imperative that low-embodied-carbon materials choices be prioritized throughout the building design process. To achieve this, this professional project creates an Excel-based, open source, and user-friendly tool for the construction sector to make design decisions that prioritize the sustainability of structures, as one such tool does not currently exist. The use of OpenLCA software and the EcoInvent34 database are utilized to calculate the environmental impact of 25 different building materials, as well as energy and electricity consumption. Swanton Pacific Ranch (SPR) in Santa Cruz County is utilized as a case study site. This is accomplished through the comparison of two hypothetical structures to test the validity and user-friendliness of the excel-based tool, and make edits and improvements as needed based on feedback. From this process, the benefits of the tool, as well as areas for its continued improvement are discussed.

Keywords: life cycle analysis, life cycle design, embodied carbon, building materials, sustainable building design.

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TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Chapter 1

INTRODUCTION

Carbon is the primary greenhouse gas contributing to a changing climate (US EPA, 2021). Increases in average global temperatures are expected to be between 0.5°F to 8.6°F by 2100, with a likely increase of at least 2.7°F (*Climate Change,* 2013). Additionally, the global average temperature is expected to warm at least twice as much in the next 100 years as it has during the last 100 years (*Climate Change,* 2013). A warmer climate means an increased likelihood for fire events, lower water availability, rises in ocean temperature and level, shifts in ecosystem characteristics, and more, which are all cause for concern for the health of both humans and the planet (US EPA*,* 2021).

The built environment contributes to 40% of global carbon emissions annually (Adekanye et al., 2020). To combat this, sustainable building design has emerged as a tool for creating a more resilient society that is prepared to battle and mitigate the impacts of climate change (Meacham & McNamee, 2023). An important component of sustainable building design is the utilization of building materials with lower embodied carbon (Cabeza et al., 2013). "Embodied Carbon," is defined by the Carbon Leadership Forum (CLF) as, the greenhouse gas emissions arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials (Himes, 2020).

If buildings utilize low embodied carbon materials, this provides an opportunity to reduce the atmospheric carbon contribution of the built environment (Basyigit et al., 2021). If this is consistently accomplished, and buildings contribute less carbon to the atmosphere, there is the potential to lower the impacts of climate change in the long term (Whole Building Design Guide, n.d.). The Rocky Mountain Institute explains that reducing embodied carbon emissions is an effective and immediate way to take climate action, as the majority of emissions occur before a building's construction phase (Mills, 2023).

To achieve low embodied carbon building design goals, a tool like Life Cycle Analysis (LCA) would be used because it has the capability to evaluate potential environmental impacts of a product, material, process, or activity (Vassalo, 2021). In this case, LCA would be utilized in a form known as "Life Cycle Design" (LCD). LCD can be utilized as a decision-making tool for low embodied carbon building material types. It can be understood that LCD is a necessary component to the building design process. It is conducted prior to any construction, where LCA, as mentioned above, often occurs following construction.

The issue, however, is that there is a lack of life cycle tools that are user-friendly to individuals of all backgrounds, and allow users to make material decisions in the design phase of construction (e.g., available tools perform LCA and not LCD) (Pollini & Rognoli, 2021). This is especially concerning because it has been estimated that 80% of the environmental impact of a product or service is determined in the design phase (Thackara, 2014).

Determined through a literature review, publicly available life cycle tools for carbon calculation of building designs are tools that require specific design details (i.e., number of windows in the design, type of carpet or flooring being utilized, etc.). These tools include the Athena Impact Estimator for Buildings, the Building Life Cycle Cost Program, One Click LCA Carbon Designer 3D, Tally, and Building Products Calculator (See Appendix A for more details). If utilizing these carbon accounting tools, designers may struggle to choose less carbon-intensive materials, as the tools only allow the designer to understand the embodied carbon of their building *after* a detailed design has been created. Additionally, these tools cost money to use, or require a working knowledge of LCA, rendering them inaccessible to the average person. This subsequently reduces the opportunity for integration of sustainability into design decision-making (Basbagill et al., 2013).

To combat this, an Excel-based environmental life-cycle calculator for construction planning (EELCCP) is developed to assist in pre-design materials decision-making, without the need for intricate details of the building design to be effective. With the creation of the EELCCP, designers will have the ability to compare a variety of impact categories in the pre-design phase, including Ozone Depletion, Respiratory Effects, Non-Carcinogenics, Global Warming Potential, Carcinogenics, Eutrophication, Smog, Fossil Fuel Depletion, Acidification, and Ecotoxicity (LCA 2.0.1).

The EELCCP tool will then be adopted to compare the environmental implication of two different case studies proposed for Swanton Pacific Ranch (SPR) in Santa Cruz, California, under varying design schemes. SPR is a 3,200-acre teaching ranch owned by Cal Poly. SPR lost a variety of structures in the CZU Lightning Complex Fire in the summer of 2020, and is currently in the design phase of reconstruction of these structures. It is pertinent that SPR consider how they will incorporate sustainability techniques into their building designs. This creates an opportunity to utilize LCD in the form of the EELCCP to help SPR utilize materials with low embodied carbon as they rebuild. Results from this assessment can provide insights not only into the change of environmental impacts under different conceptual building designs, but also into the improvement of the EELCCP based on the user experience.

This project will address the question of how to design and develop a major facility with the minimum environmental footprint possible. The project will provide the construction sector with an Excel-based tool for future building environmental assessment performance.

Chapter 2

LITERATURE REVIEW

This literature review provides context to the reader regarding the importance of sustainability and low-embodied carbon design in the built environment. This report hopes to shed light on the need for LCD when conducting building design to mitigate the worst impacts of climate change, as well as create resilient, long-standing structures and communities. Information is provided on how building design has been historically conducted (and how it can be improved upon) and how building codes and regulations might impact design strategies. The environmental impacts of typical building design strategies are discussed, and the review concludes with a discussion of the current scenario at SPR, and an explanation of how this information allows for innovation through the inclusion of LCD.

2.1 The Built Environment and its Impact on Climate Change

Embodied carbon from building materials choice is responsible for 20% of global CO_2 emissions annually (Architecture 2030, 2021). Projections indicate that the global building floor area is going to double by the year 2060 (Architecture 2030, 2021). This means that 2.4 trillion ft^2 of new floor area will be added to the global building stock (Architecture 2030, 2021). This can be visualized as the equivalent of adding an entire New York City to the world, every month, for 40 years (Architecture 2030, 2021). The construction industry requires around 30 billion tons of materials each year, which subsequently results in the consumption of energy resources and the release of pollutant emissions (Cabeza et al., 2013). Every material that is utilized to create a new building has to be extracted, processed, and transported to its place of use. All of these steps contribute additional carbon to the atmosphere, furthering the impacts of anthropogenic climate change and global warming (Cabeza et al., 2013). With these things in mind, it is pertinent that the carbon emissions of the built environment be considered, and reduced, in all ways possible. To achieve low to zero emissions from new construction, it is important to think about emissions reduction and the avenues for achieving it to enhance the well-being of both people and the planet (Architecture 2030, 2021).

2.2 Low-Embodied Carbon and Sustainable Design of Building Materials

When designing and constructing buildings, it is important to consider the embodied carbon of material choices. Pollutant emissions, like those from CO_2, are often embodied within materials (Himes, 2020). The Carbon Leadership Forum explains that the majority of a building's total embodied carbon is released at the beginning of a building's life (see Figure 1) (Himes, 2020). This is problematic because embodied carbon cannot be decreased like operational carbon can be. Operational carbon is the greenhouse gas emissions emitted from building energy consumption, and it can be mitigated with updates in appliance efficiency after a building is constructed (Himes, 2020).

It is essential that embodied carbon be reduced, as there are stringent goals to reduce carbon emissions into the atmosphere. According to the Paris Agreement, average global temperatures must not rise more than 2°C if humans are to avoid irreversible and catastrophic climate change impacts (*Paris Agreement*, 2015). The timeline for these emissions reduction is rapidly growing smaller, meaning that it is critical that emissions be reduced as much as possible in all sectors that contribute high amounts of carbon dioxide to the atmosphere (Himes, 2020). It can be understood why choosing materials with low embodied carbon is necessary for emissions reduction and the continued well-being of the planet as well as the people and creatures that call it home.

Sustainable design in buildings has become of interest to many people throughout the world because of the large amount of energy and materials that are consumed by the construction sector. Construction activities have significant negative impacts on the environment, such as air and water pollution, and waste generation (Jaillon & Poon, 2014). In a paper from Celalettin Basyigit, et al. that evaluates the environmental effects of sustainable building materials use, it was found that population density has a direct impact on housing, because, as more humans populate the planet, more infrastructure will be necessary to support their needs (Basyigit et al., 2021). It can be understood that there will be an increase in CO_2 emissions from additional buildings being constructed to support population growth.

Many environmental problems are directly linked to the construction industry (Jaillon & Poon, 2014). For example, concrete, steel, and insulation are all examples of materials that contribute to embodied carbon emissions, because they account for 11% of global greenhouse gas (GHG) emissions (Mills, 2023). Therefore, it is imperative that sustainable design be prioritized to truly decrease embodied carbon emissions and increase the health of people and the planet. As part of this literature review, options for other types of building materials that do not have high embodied carbon amounts were analyzed. Some examples include recycled aggregate concrete, alkali bricks, and agricultural wastes such as coconut shells, jute fiber, and rice husks. Hemp, straw, bamboo, and algae are popular alternative material choices as well (*Biofilico, 2018*). Material choice in building design is a substantive part of embodied carbon reduction, and something that hopes to be brought to light with the fruition of this research.

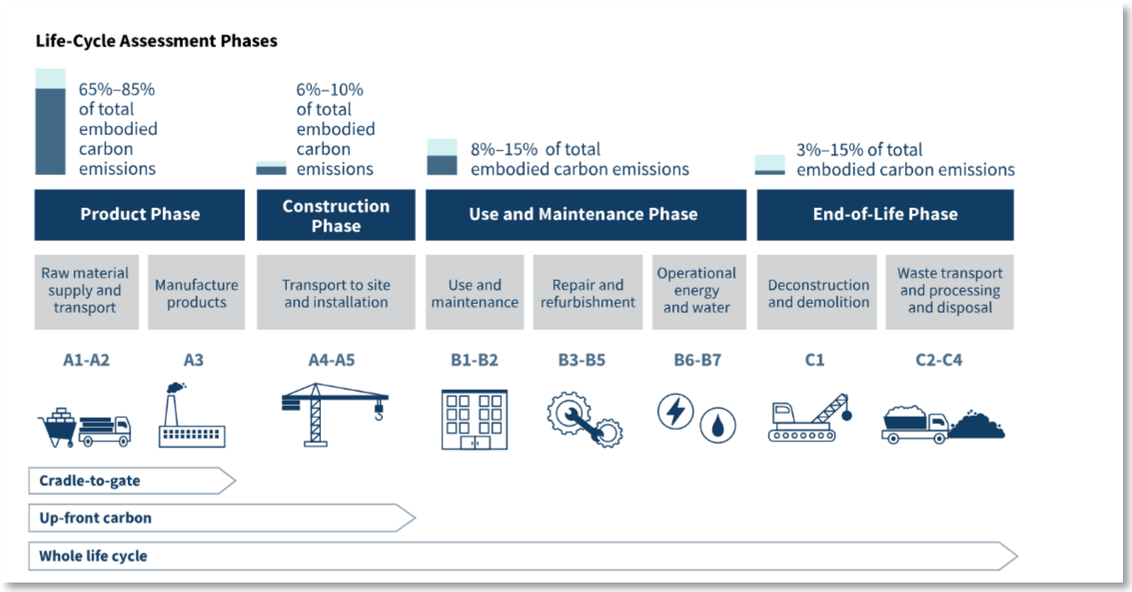

Figure 1: Visualization of Embodied Carbon Emissions Life Cycle (Rocky Mountain Institute, 2023)

2.3 Life Cycle Design and the Built Environment

LCA is a tool that can be very powerful in the construction sector. It is often used as a decision-making tool for sustainable development, and can be utilized to help assess any direct and indirect environmental impacts across the entire life cycle of something (Vassalo, 2021). The life cycle that can be analyzed includes materials acquisition, manufacturing, use, and disposal. This is typically referenced as “cradle to grave” (Brusseau, 2019).

Utilizing LCA helps ensure that sustainable design is prioritized when creating new products or materials. This prioritization can lead to a reduction in overall environmental impacts and reduction of nonrenewable and toxic materials (Brusseau, 2019). LCA helps to reduce the necessity of resources while also supporting human health (Brusseau, 2019). The process of LCA includes: (1) goal definition and scoping, (2) inventory analysis, (3) impact assessment, and (4) interpretation (Ding, 2014). Goal definition and scoping includes a description of the product and provides context for why the assessment is necessary (Vassalo, 2021). Inventory analysis helps to identify and quantify how energy, water, and materials use release pollutants like air emissions, solid waste, and wastewater discharge into the environment (ScienceDirect, 2017). The impact assessment portion assesses how humans and ecology influence the items identified in the inventory analysis (ScienceDirect, 2017). Finally, the interpretation evaluates the results of the inventory analysis and impact assessment to help in the selection process for materials and design(ScienceDirect, 2017).

Through the utilization of an LCA, it is easier to develop terms of evaluation for any environmental consequences associated with products, analyze environmental and cost tradeoffs of a product, and quantify any major environmental releases of a product from its stages of production (Brusseau, 2019). Additionally, you can directly compare the health and ecological impacts of two or more products to one another (Brusseau, 2019).

LCA can be utilized for more than just the design of individual products. For example, the LCD process takes an interdisciplinary approach and analyzes environmental impacts *before* the completion of a product (Climate Technology Centre & Network, 2016). LCD is not often used because of a lack of incentive for this additional step in the design phase of a product (Adeyeye et al., 2007). In the building sector specifically, there is not a user-friendly, open-source tool to assess environmental impacts in early design phases. Rather, there are tools for LCA of structures post-construction. This creates a need for LCD to become more readily used when creating new building infrastructure. The utilization of LCD helps to make design phase decisions, such as built form, orientation, design features, building materials, structural systems, and mechanical and electrical equipment, easier to decide upon (Climate Technology Centre & Network, 2016). LCD helps to consider a product's embodied energy, performance, lifecycle, cost, lifespan, and what happens to it after life (Climate Technology Centre & Network, 2016).

2.4 Incorporation of Swanton Pacific Ranch as a Case Study

When creating the EELCCP, SPR's *As Was Plan* written by Siegel & Strain Architects, et al., served as an important resource. The report was prepared to, "Create an accurate description of the size, type, quality, and quantity of structures and systems lost at SPR (in the CZU Lightning Complex Fire)" (Siegel & Strain Architects, 2022). The report is organized into seven areas, with the following information included in each: (1) area site diagram & building key, (2) area utility & site features descriptions, (3) building descriptions, (4) area site and floor plans, and (5) program table (Siegel & Strain Architects, 2022).

To aid in material choice for the EELCCP's database, research was focused on the Al Smith House and the Staub House. It is valuable to note the types of materials that these structures were originally built from. Often, when dealing with insurance, companies no longer offer "guaranteed replacement," and will only pay to replace the exact same type of material that was originally used (Johnson, 2023). This means that the cost of any extraneous material types, such as ones that might have a lower carbon footprint than the types initially utilized, would fall on SPR to pay for, and not on the insurance company. When conducting the LCD for this project, the original materials used were input into the software and compared against other types of materials that may be categorized as alternative. For reference, the Al Smith House was originally constructed out of old growth redwood, stone, concrete, clay, and aluminum. The Staub House was originally constructed out of asphalt, wood, aluminum, brick, and fiberboard.

2.5 Material Choices for LCD Data Analysis

The materials chosen for LCD data analysis were determined through desktop research (see Section 3.4). Below is a table listing the materials from the SPR *As Was Plan*, conventional building materials, and alternative building materials. In the context of this research, "conventional" is interpreted as materials that have been historically and widely used in construction. "Alternative" is interpreted as materials that are less commonly used, and typically bio-based.

Table 1: Materials Selection

***As Was Plan* Materials**	**"Conventional" Building Materials**	**"Alternative" Building Materials**
Aluminum	Aluminum	Clay Plaster
Asphalt	Asphalt	Cob
Brick	Brick	Jute
Clay	Cement	Mineral Wool
Concrete	Ceramic Tile	Woodchips
Fiberboard	Concrete	
Redwood	Copper	
Stone	Expanded Polystyrene	
	Extruded Polystyrene	

	Glass (coated)	
	Glass (uncoated)	
	Gravel	
	Gypsum Board	
	Limestone	
	Plaster	
	Polyurethane Insulation	
	PVC Pipe	
	Steel	
	Wooden Boards	

2.6 Concluding Remarks

Given this information, there is a need for Life Cycle Design to be an integral part of the building design phase. Without its inclusion, the construction sector is left with little guidance on how to reduce their embodied carbon footprint. This project connects the dots between the greater importance of green building design and what some strategies for implementation of it are. The following section will explain the methods for conducting the Life Cycle Design for the specific built environment case studies at SPR.

Chapter 3

METHODS & DATA

3.1 The EELCCP

3.1.1 Purpose

As the output of this research, an Excel spreadsheet tool was created. The EELCCP tool will serve as a resource for architects and engineers as they move to make preliminary building design decisions. The EELCCP tool is in an Excel sheet format for ease of use by individuals of all backgrounds. This format allows for interpretation of LCA data without having to have a background in LCA. Users will be able to input how much (in mass or volume) of any of the materials they plan to use, and the EELCCP will show them the results for each impact category. This information will help users to make informed decisions about the tradeoffs of utilizing various material types.

3.1.2 Creation

The logic for the creation of the EELCCP is visualized in Figure 2 below. To acquire data to build out the database, a literature review and interviews were conducted (see Section 3.4 for details). From this information, primary materials for construction were determined. These materials include a mix of materials from the SPR *As Was Plan* written by Siegel and Strain Architects, et. al., as well as a list of 'conventional' materials and 'alternative' materials (see Section 2.5 for definitions) that were determined through desktop research and interview data. From this, the LCA footprint per unit of each material was determined using OpenLCA 2.0 software along with the EcoInvent34 database. The EELCPP tool was developed in Excel with 5 tabs: *User Input, Calculate Impact, Base Impact Data, Unit Conversion,* and *References*. The EELCCP then went through multiple rounds of testing through the utilization of the SPR Case Studies, so as to better understand how to make the tool user friendly and with data that is relevant and helpful to the construction industry. As testing went on, new materials to be analyzed were uncovered, or edits for the user interface were determined, and these were integrated into the EELCCP design and tested once again.

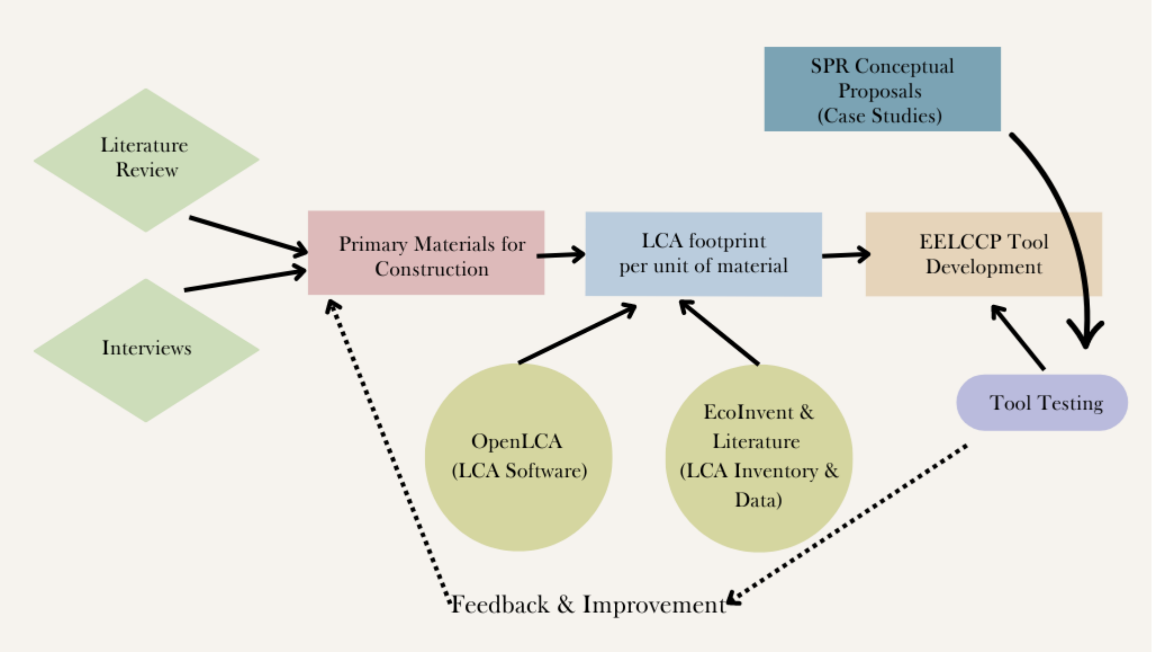

Figure 2: EELCCP creation procedure flowchart, created by Hope Springer with guidance from Dr. Yiwen Chiu

3.2 Case Study Site Selection

The site for the tool testing case study is Swanton Pacific Ranch (SPR/The Ranch). SPR is a 3,200-acre working ranch, located in Santa Cruz County, overlooking the Pacific Ocean and scenic Highway 1. The Ranch was donated to Cal Poly in 1993 by the late Mr. Al Smith, who was a Cal Poly graduate and founder of Orchard Supply Hardware. Through acceptance of this donation, Cal Poly continuously ensures that the ranch is, "maintained as a working ranch and used exclusively for agriculture, recreational, and educational purposes" (Springer, & Forstmann, 2022).

The Cal Poly Corporation owns The Ranch, and it is managed by the College of Agriculture, Food and Environmental Sciences (CAFES) for pursuing research and educational opportunities, and practicing "Learn by Doing" in hands-on courses. As a university resource, The Ranch focuses on relationship building, hands-on experiences, and more, in applied and technical land management, including resource production and applied research. Collaborative natural resource management that promotes a Learn by Doing atmosphere is prioritized (Springer, & Forstmann, 2022).

Located within a biodiversity hotspot of national and global significance, created by its Mediterranean climate, fog, and ecological history, SPR is a location of academic and ecological value. Together with its immediate environs, The Ranch supports a wealth of biota, while supporting land management practices that derive benefit from natural resources. Some of the species and ecosystems of SPR are biologically rare or endangered, while others have been recognized as locally significant or have traits that also suggest a need to prioritize their conservation (Springer, & Forstmann, 2022).

In August of 2020, the CZU Lightning Complex Fire swept through Santa Cruz and San Mateo counties. Ignited by a lightning strike, this fire burned quickly through the drought-stricken landscape. The fire destroyed 24 structures at SPR and heavily damaged the forested land. The people and livestock on the ranch were all safely evacuated, and the organic apple orchard and "Casa Verde," the bunkhouse, and the "Cowboy Shack" buildings survived the fires (Springer, & Forstmann, 2022).

Although the fires were devastating, they provided an opportunity for The Ranch to reimagine its operations entirely. SPR and its community members are planning for a more resilient future with increased student involvement, increased monitoring, and a deeper connection with its community (Springer, & Forstmann, 2022).

Currently, SPR and its managers are focused on rebuilding. With such a rich history of community education and involvement, as well as its designation as a biodiversity hotspot, it is pertinent that the Ranch be able to house and host Cal Poly community members for research and educational opportunities again soon. The Strategic Intent for Cal Poly's Swanton Pacific Ranch is, "to develop exceptional leaders through interdisciplinary, whole systems thinking and Learn by Doing practice to bring about sustainable, long-term solutions to the management and stewardship of working landscapes" (Springer, & Forstmann, 2022). To maintain the integrity of this intent, there is a need for sustainable and resilient rebuild.

Given this statement, Dr. Yiwen Chiu (Cal Poly Life Cycle Analysis professor) and Dr. Grey Hayes (Ecological & Education Director for SPR) decided that materials choice for structure rebuild would play a large role in the sustainability and resiliency of The Ranch moving forward. With the concept of 'Learn by Doing' in mind, this project was proposed as a graduate professional project to help SPR as they work on their rebuild. This project will use SPR as a case study to help them understand how they can design and develop a major facility with the minimum environmental footprint possible. The final product will provide the construction sector with a decision-making tool to achieve sustainability.

3.3 Sampling Frame

The sample size for this project includes potential building materials that may be used at SPR during the rebuild (see Table 1 for a complete list of materials). These building materials are a mixture of conventional material types, as well as some alternative materials that are less widely used, but are being assessed to compare their “sustainability statistics” to the materials that have a higher volume of use during construction (see Section 2.5 for definitions of ‘conventional’ and ‘alternative’). This sampling frame was constructed through desktop research and key informant interviews. Certain materials were suggested during interviews or uncovered during desktop research based on their resistance to fire and/or global warming potential (embodied carbon).

3.3.1 Limitations

Limitations are a factor that influence the ability to conduct this research. For example, there was a lack of initial knowledge in understanding the qualities of different types of building materials, building code and its applications, fire resilient design elements, and other background elements regarding building design choice. This created the necessity for desktop research and interviews with key informants to fill this knowledge gap. Additionally, the above sampling decisions may not provide the full breadth of materials that SPR could use for rebuild, as there may be biased information given by key informants. For example, an informant with a background in one discipline may make recommendations based on their particular field of knowledge, without consideration for other factors. Due to the lack of baseline knowledge on the topic of building design and material qualities, there may be an overreliance on the validity of the information the informants are providing. Additionally, there is the potential that the desktop research was not broad enough and therefore the information is based off a small sample pool of online and printed information.

3.3.2 Ethics

Additional to the sampling frame is the discussion of ethics. Although this project does not cover the scope of construction, it is still pertinent that ethics be included so that they may be considered by those in the construction sector as they move to break ground and build. For example, the case study site, Swanton Pacific Ranch, sits on the traditional land of the Amah Mutsun tribal band. With this information in mind, it is important that a historical artifacts survey be conducted at each location being developed on prior to the start of construction. Additionally, a noise and air pollution survey should be conducted prior to construction to ensure that the volumes of these pollutants are not so high as to be disturbing to the species that make up the rich biological diversity of The Ranch.

3.4 Data collection

3.4.1 Interviews & Desktop Research

For desktop research, the materials needed include internet access, a computer, relevant literature (books, magazines, etc., on sustainable building design), and institutional/library access to literature. For the key informant interviews, the materials needed include information on who to talk to, Zoom access for virtual interviews, knowledge of key information to ask, vehicle access for in-person interviews, notebook/pen for notes, computer to transcribe notes into online format, and a recording device (ex: phone) to record interview. Desktop research was conducted through the reading of primary literature (websites, magazines, books, journal articles, etc.).

Interview research was also conducted. Below, in Table 2, a list of interviewees can be found along with the logic for conducting each particular interview, and pertinent data that was collected. Data collected via Zoom have been put directly into a OneDrive notebook, and data collected in the field (in-person interviews) have been transferred from a handheld notebook to the OneDrive notebook so that all data is in a single, consistent spot.

Table 2: Interviewees with Reasoning & Takeaways

Interviewee	**Date of Interview**	**Interview Details**
Liza McNulty	October 17, 2022	Liza McNulty was the primary interviewee because of her role as the lead engineer and project manager for the rebuild of structures at SPR. Liza provided information about FEMA and insurance funding for the rebuild. She also provided a PDF copy of the "As-Was-to-Code" plan that will be referred to during rebuild. Building code and WUI code (and the materials necessary to adhere to them) were discussed during this interview as well.
Professor Stacey White	October 19, 2022	Stacey White, an architecture and planning professor, was interviewed because of her involvement with student-led projects regarding fire resilient building design, specifically for rebuilding following the Paradise, CA fire (Cal Poly News, 2019). Professor White provided suggestions for resilient design (electrification of buildings, implementation of infrastructure for evacuation, undergrounding utility lines, and metal building exterior cladding). These insights helped streamline desktop research searches when looking into fire-resilient building materials and design.

Professor Miran Day	October 20, 2022	Landscape Architecture professor Miran Day was interviewed because of her leadership on a project that her Spring 2022 Natural Systems Design Studio students worked on. For this project, Cal Poly students created climate-change-resilient designs for the rebuild of structures at SPR (Cal Poly News, 2022). This information from Professor Day was helpful to refine understanding of material choice when creating a fire-resilient structure. Additionally, building design renderings from her Spring 2023 *GIS Application to Design Products* course were used as part of the case study for this research project.
Professor Jonathan Reich	January 25, 2023	An interview was conducted with architecture professor Jonathan Reich to learn about a project that a previous cohort of his students worked on to design a fire resilient student housing structure for SPR. This interview was important to learn about the logic of building material choices, as the students factored in sustainability and resiliency.
Niles Wertz	February 10th-13th, 2023	A weekend was spent at SPR with architecture student Niles Wertz because he was in the process of building the first new structure (a fire resilient storage shed) at SPR post-CZU fire. Help building the structure was

		provided in exchange for firsthand knowledge from Niles regarding building materials selection and design for resiliency.
Susi Marzuola	June 6, 2023	Susi Marzuola, a Partner at Siegel & Strain Architects, was interviewed because of her firm's involvement with the building design of the Education Center at SPR. Susi and her firm have worked closely with The Ranch to create a vision of what it might look like moving forward. She provided insight to the firm's design decisions, material choices, and building location propositions.

3.4.2 Materials Selection

The materials utilized in the EELCCP tool database (see Table 1 for details) were determined based on information from the interviews and desktop research that were conducted. If specific materials were mentioned in interviews, these were taken note of. Desktop research was conducted to gather a list of the most commonly used conventional and alternative building materials. The finalized materials list (see Table 1) was decided upon based on EcoInvent data availability as well as practicality for use by designers in the EELCCP tool. Each material was searched in the EcoInvent database to ensure that data was available to be analyzed. Then, a cross-check was done with a review of literature to ensure the material would be useful for users to have access to.

3.5 Data archiving

Interview data is in a OneDrive notebook so that it is online and may be revisited at any time. Interview recordings have been transcribed and uploaded to the OneDrive notebook as well. Original, handwritten interview notes have been kept in their respective notebooks, but transcribed to the OneDrive notebook, so as to have all notes in one place. Desktop research has been archived in its own folder and tab within the same OneDrive notebook. Unit processes created in OpenLCA are in a folder within the software titled "EELCCP tool database." The EELCCP tool itself also serves as a data archive, with *Base Impact Data* and *Unit Conversion* tabs that hold Life Cycle Impact (LCI) data results of each material, and common conversion factors, respectively.

3.6 Data Analysis

Qualitative interview data was analyzed by highlighting key concepts from each interview for further research. Notes were made about any material and resiliency choices that were continuously mentioned in conversation. Additionally, notes were made regarding individuals who might be helpful to reach out to for additional knowledge.

Building materials data was analyzed using OpenLCA software and EcoInvent34 Tool for Reduction and Assessment of Chemicals and other environmental Impacts (TRACI) data. In Table 3 below, the logic for data analysis can be visualized. Each material was analyzed in OpenLCA by first checking if it had an existing unit process. If yes, then that unit process was utilized as the "input" and a new flow with the material name was set as the "output." The data provider was chosen by region. Data from the United States (US) was prioritized, with Global (GLO) data second. If neither of these were an option, all provider regions were chosen (ex: Switzerland (CH) and Rest of World (RoW)) and a quick desktop search was conducted to create a ratio for the amount of material that is produced by each region. If a unit process was not already available, one was created utilizing data available in EcoInvent to create the desired input. A desktop search was conducted to determine proper ratios of input materials to create a single unit process. Provider regions and ratios are recorded for each material in Table 3 below. Once the input and output tables were settled with the correct data, providers, and ratios, a product system was created for each material. Then, the impact of each product system was calculated, using a "Lazy/On-demand" calculation type. This calculation provides a table with LCI data. The LCI output for each material analyzed was copied into the *Base Impact Data* tab in the EELCCP that was created as the output of this research.

The *Base Impact Data* and *Unit Conversion* tabs in the EELCCP tool were created by Hope Springer, with guidance from Dr. Yiwen Chiu. The coding for the *User Input* and *Calculate Input* tabs were performed by Dr. Yiwen Chiu. *References* were updated by both Springer and Chiu.

Table 3: OpenLCA Data Analysis Logic Model for Building Materials

Material	**Existing Unit Process?**	**Region(s)**	**Ratios**
Aluminum	Y	GLO	1kg
Asphalt	Y	GLO	1kg
Brick	Y	GLO	1kg
Cement (Portland)	Y	US	1kg

Ceramic Tiles	Y	GLO	1kg
Clay Plaster[1]	Y	CH RoW	CH – 0.3kg RoW – 0.7kg
Cob (clay, sand, straw)	N; unit process was created based off typical clay, sand, & straw ratios[2]	CH RoW GLO	Clay (CH) – 0.05 Clay (RoW) – 0.1 Sand (GLO) – 0.8 Straw (GLO) – 0.05
Concrete[3]	Y	CH RoW	CH – 0.3kg RoW – 0.7kg
Copper	Y	GLO	1kg
Expanded Polystyrene	Y	GLO	1kg
Extruded Polystyrene	Y	GLO	1kg
Fiberboard[4]	N; unit process was created for indoor and outdoor	GLO	Indoor – 0.5m^3 Outdoor – 0.5m^3

---

[1] Ratio is an assumption of this study.

[2] (Ziggy, 2015)

[3] Ratio is an assumption of this study.

[4] Ratio is an assumption of this study.

	particleboard use		
Glass (flat, coated)	Y	GLO	1kg
Glass (flat, uncoated)	Y	GLO	1kg
Gravel[5]		CH RoW	CH – 0.4kg RoW – 0.6kg
Gypsum plasterboard	Y	GLO	1kg
Jute Fiber	Y	GLO	1kg
Limestone[6]	Y	CH RoW	CH – 0.3kg RoW – 0.7kg
Mineral Wool for Insulation	Y	GLO	1kg
Plaster	Y	GLO	1kg
Polyurethane Insulation[7]	N; unit process was created by combining data for both flexible and rigid foam	GLO	Flexible – 0.5kg Rigid – 0.5kg

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[5] Ratio is an assumption of this study.
[6] Ratio is an assumption of this study.
[7] Ratio is an assumption of this study.

Polyvinyl Chloride (PVC)	Y	GLO	1kg
Steel	Y	GLO	1kg
Woodchips[8]	N; unit process created by combining data for softwood and hardwood usage	RoW	Softwood – 0.71kg Hardwood – 0.29kg
Wooden board[9]	N; unit process created by combining data for softwood and hardwood usage	GLO	Softwood – $0.78m^3$ Hardwood – $0.22m^3$

3.7 Data Validation

Data validation was performed multiple ways. First, it was done by cross-checking outputs of the EELCCP with Life Cycle Impact Assessment (LCIA) study results. For example, the output of annual air conditioning and lighting consumption was compared to that of an annual national report. LCI results from OpenLCA were also validated by comparing their values to those of published LCIA study results. Specifically, the global warming potential

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[8] Ratios sourced from (Alderman et al., n.d.).

[9] Ratios sourced from (Alderman et al., n.d.).

of concrete was compared to the results of a published study. Performing the case study also served as a form of data validation. Results of validation are discussed in Chapter 5.

3.8 Case Study

To aid in the understanding of the data validity and user friendliness of the EELCCP tool, two case studies utilizing hypothetical building scenarios at SPR were utilized. The details of both case studies can be seen below in Tables 4 & 5 and Figures 3 &4. Materials were chosen by the author, with one case study utilizing a majority 'alternative' materials, and the other utilizing mainly 'conventional' construction materials (See Section 2.5 for definitions). The size of the structures and room types were determined on assumption from desktop research data. The values for material choices were determined based on desktop research of typical building material ratios for each respective square footage. The building design renderings were provided by students in Dr. Miran Day's Spring 2023 *GIS Application to Design Projects* course. Results and discussion of the case study follow in Sections 4 & 5.

Table 4: SPR Case Study #1

Case	**Total Square Footage of Structure**[10]	**Total Area of Site**[11]	**Materials Used**[12]	**Room Types**[13]
#1: Student Housing	1000 sq-ft	3,000 sq-ft	• Cob • Concrete • Woodchips	4 bedrooms (200 sq-ft each)

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[10] Assumption (Room Sketcher, 2023).
[11] Assumption (Natale Builders, 2022).
[12] Materials choices made by author.
[13] Assumption (Student Room Stay, 2021).

			• Wooden board • Glass (coated & uncoated) • Mineral Wool Insulation • Brick • Ceramic tiles • Clay plaster	2 bathrooms (100 sq-ft each)

Data Entry	**Value**
Area	
Site Area Size	3000ft^2
Total Stories (above ground)	1
Total area (aboveground)	1000ft^2
Bedroom area	800ft^2
Bathroom Area	200ft^2
Energy	
Energy Saving Target	5% reduction
Expected lifespan of the building	50 years
Materials Choice	
Brick	112,000lb

Ceramic Tiles	2,000lb
Clay Plaster	6,000lb
Cob	33,704gal
Concrete	12.5yd^3
Glass (coated	50ft^3
Glass (uncoated)	100ft^3
Mineral Wool	423.3ft^3
Woodchips	12.3yd^3
Wooden Board	3600lb

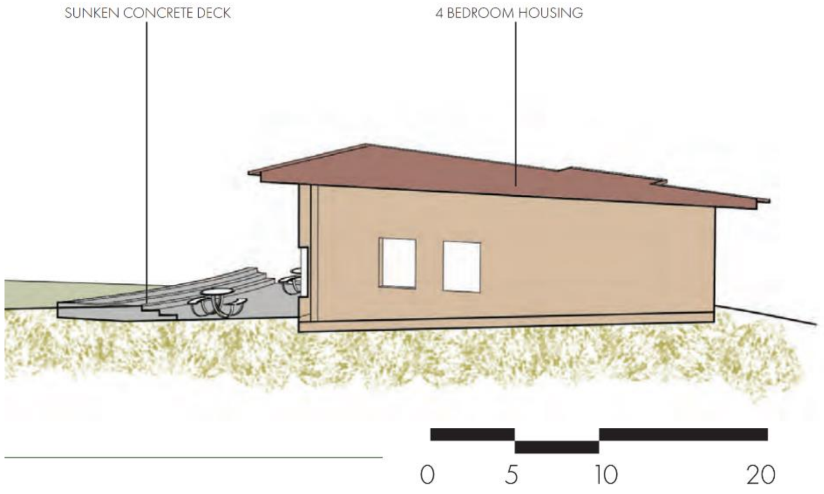

Figure 3: Student Housing Design Rendering

Source: Kayla Parrish and Kiley Cook with guidance from Dr. Miran Day, GIS Application to Design Projects, Spring 2023

Table 5: SPR Case Study #2

<table>
<tr><th>Case</th><th>Total Square Footage of Structure[14]</th><th>Total Area of Site[15]</th><th>Materials Used[16]</th><th>Room Types[17]</th></tr>
<tr><td>#2: Multipurpose Space</td><td>2,500 sq-ft</td><td>7,500 sq-ft</td><td>• Asphalt
• Gravel
• Cement
• Concrete
• Glass (coated and uncoated)
• Plaster
• Fiberboard
• Polyvinyl chloride
• Wooden board</td><td>Classroom (800 sq-ft)
Kitchen Space (500 sq-ft)
Community Space (1,000 sq ft)
4 bathrooms (50 sq-ft each)</td></tr>
<tr><td colspan="3">Data Entry</td><td colspan="2">Value</td></tr>
<tr><td colspan="5" align="center">Area</td></tr>
</table>

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[14] Assumption (Room Sketcher, 2023).

[15] Assumption (Natale Builders, 2022).

[16] Materials choices made by author.

[17] Assumption (Community Enterprise Center, 2023).

Site Area Size	7500ft^2
Total Stories (above ground)	1
Total area (aboveground)	2500ft^2
Kitchen	500ft^2
Bathroom Area	200ft^2
Classroom	800ft^2
Multipurpose Space	1000ft^2
Energy	
Energy Saving Target	5% reduction
Expected lifespan of the building	50 years
Materials Choice	
Asphalt	23ton
Cement (Portland)	3.2yd^3
Concrete	32yd^3
Fiberboard	1,057.5ft^3
Glass (coated)	125ft^3
Glass (uncoated	250ft^3
Gravel	10ton
Plaster	30,000lb

Wooden Board	9000lb

Figure 4: Multipurpose Space Design Rendering

Source: Amanda Park and Erin Werkmeister with guidance from Dr. Miran Day, GIS Application to Design Products, Spring 2023

Chapter 4

RESULTS

4.1 EELCPP Tool Presentation

EELCCP tool coding was completed by Dr. Yiwen Chiu. The finished EELCCP tool is in Excel, with 5 tabs of data including, *User Input, Calculate Impact, Base Impact Data, Unit Conversion,* and *References.* A diagram showcasing the logic of the *User Input* tab of the tool, with an explanation of its functions is showcased below.

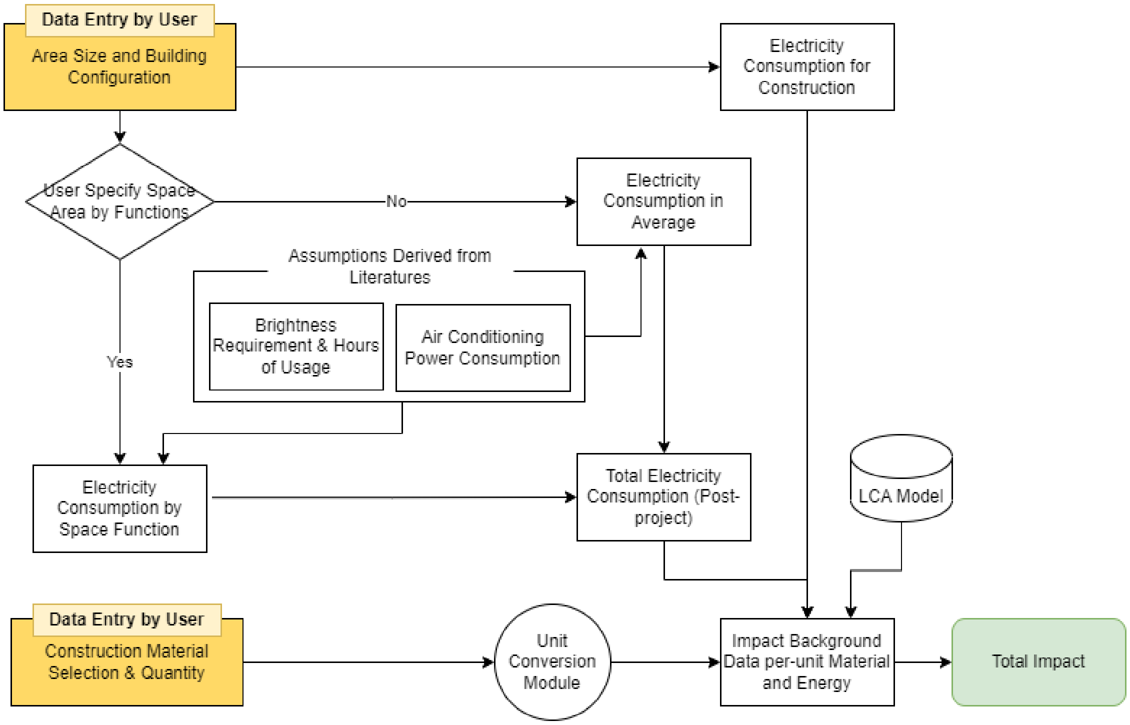

Figure 5: EELCCP Logic Diagram, created by Dr. Yiwen Chiu

Upon opening the tool in Excel, the user enters any baseline data that is available for their project. Users can choose the expected lifespan of their building, along with their energy saving target in percent. When entering project area and building configuration (number of stories), the user can choose whether they would like to share area of each individual room, including garage or parking lot, kitchen, bathroom or restroom, office, dining room, living room, and bedroom. If the user answers yes, they are prompted to enter these values. The electricity consumption is then automatically calculated based off the area values for each space. These values are derived from lighting brightness requirements and hours of usage, and air conditioning power consumption assumptions determined through desktop research. If no, electricity consumption for the space will be calculated based off an average value for the total area of the building. These values are derived from the same assumptions. The electricity consumption during the construction phase of creating a new building is determined by the total area of the site. This data comes from a regression equation derived by Dr. Yiwen Chiu that defines a relationship between floors (number of building stories), total footage (in m^2), and construction electricity consumption in kwh based off literature. This regression analysis shows that utility power for building construction can be estimated as: $kWh=553.9169-6.0164*floor-0.0006*sqm$, where floor is equal to total stories of a building, and sqm is the total footage of a building in m^2. In this scenario, R2 comes to 0.86, showcasing the goodness of the fit.

For site preparation, the assumption is that there is 1 meter (m) of digging depth that will occur, regardless of how large the structure is. Additionally, there is an assumption of 2.5m ceiling heights, with a recommendation that the foundation be 1/3 of the height of the structure. Therefore, if the user specifies additional stories on the building, the foundation will be deeper, requiring more site preparation to achieve this. For any open areas without structure, it is assumed that there is 0.5m depth of site preparation.

To calculate electricity consumption for each specific room, the sum of area size per space is multiplied by the assumption of kilowatt hours of operation per day, for both air conditioning and lighting on an annual basis. If an area size is not specified, a default average is assumed. Daily hourly use for lighting was an assumption of this study. Lighting energy consumption of each room was calculated through the recommended number of footcandles for each specific space (see Table 6 below) divided by the conversion factor for square feet to square meter of space.

Table 6: Recommended Footcandles per Room

Room	**Recommended Footcandles**
Garage	90
Kitchen	75
Bathroom	75
Office	70
Dining Room	35
Living Room	15
Bedroom	15

Following the building and site questions, the user can enter information for the building materials they would like to use in their project. There is a list of 25 commonly used building materials (see Table 1 for the full list) and users can enter the amount of each material that they will be utilizing. Users also have the flexibility to choose from 11 different units of volume and mass to quantify their material amounts. Once these values are entered, the data goes through unit conversion so that results are normalized with either kilograms or square meters as their unit. These are the units that the LCA model data were derived in.

The total electricity consumption (post-project), electricity consumption for construction, and building material amounts data are combined to calculate the total impact, with 10 different impact categories to compare. Looking at the *Calculate Impact* tab, the user can see these results, along with the impact of site preparation. Users are also shown their annual impact (based on the projected lifespan of the building) pre-project and post-project. Users can see the percent breakdown of materials, site preparation, and electricity consumption with direct impact category comparisons.

4.2 Case Study Results

The case studies of a hypothetical student housing structure and a multipurpose space at SPR (see Section 3.8 for full case study details) were used to test the EELCCP tool for data validity and user friendliness.

Values for the materials in each case study were derived from a literature review of typical material ratios for construction. Case Study #1 utilizes 'alternative' materials like cob, woodchips, clay plaster, and mineral wool. Case Study #2 utilizes higher volumes of 'conventional' materials, like gravel, fiberboard, plaster, and asphalt.

Based on these inputs, the impact results are as expected. Case Study #2 has higher Total Impact in all impact categories than Case Study #1 (See Appendices B & C for full tables of results). It is important to keep in mind that the structure in Case Study #1 is 1500ft^2 smaller than Case Study #2 and the site is 4500ft^2 smaller. This means that the lower impact results of Case Study #1 cannot be solely attributed to alternative material choice. Considering the purpose of this particular case study was to test the EELCCP tool for data validity and user friendliness, and not specifically to compare material choice, the purpose of the study was met. Further discussion of these results will follow in Chapter 5.

The figures below provide visualization to compare different aspects of each case study. Figure 6 depicts the 5 inputs for each case study that contribute the highest GHG emissions, with electricity throughout the user phase having the highest contribution for both scenarios. It is understandable that Case Study #2 has a higher percentage of electricity usage, considering the structure is a larger square footage. Figure 7 shows the amount of forest acreage at SPR required to completely offset the GHG emissions for each structure over a 50-year lifespan. For the approximately 24 acres required for complete GHG offset of these structures, there are 2100 acres of forested land at SPR available as carbon sinks. This equates to 1.14% of the total forested land. Figure 8 presents the global warming potential (GWP) for 1 square meter of space in each structure, with 126.2 $kgCO_2eq$ per square meter and 87 $kgCO_2eq$ per square meter for Case Study #1 and Case Study #2, respectively. When compared to published literature, these values are high. In a study from Rock, et. al., it was found that existing residential buildings have an average $kgCO_2eq$ per square meter of 6.7-11.2. While these values are higher than what is calculated for the case studies in this professional project, it is important to note that the buildings evaluated in the Rock, et. al., study are considered "energy-efficient." Currently, Version 1 (V1) of the EELCCP only accounts for air conditioning use, and assumes that the air conditioning is running 365 days a year, meaning that the case studies evaluated for this report do not hold the same level of energy efficiency.

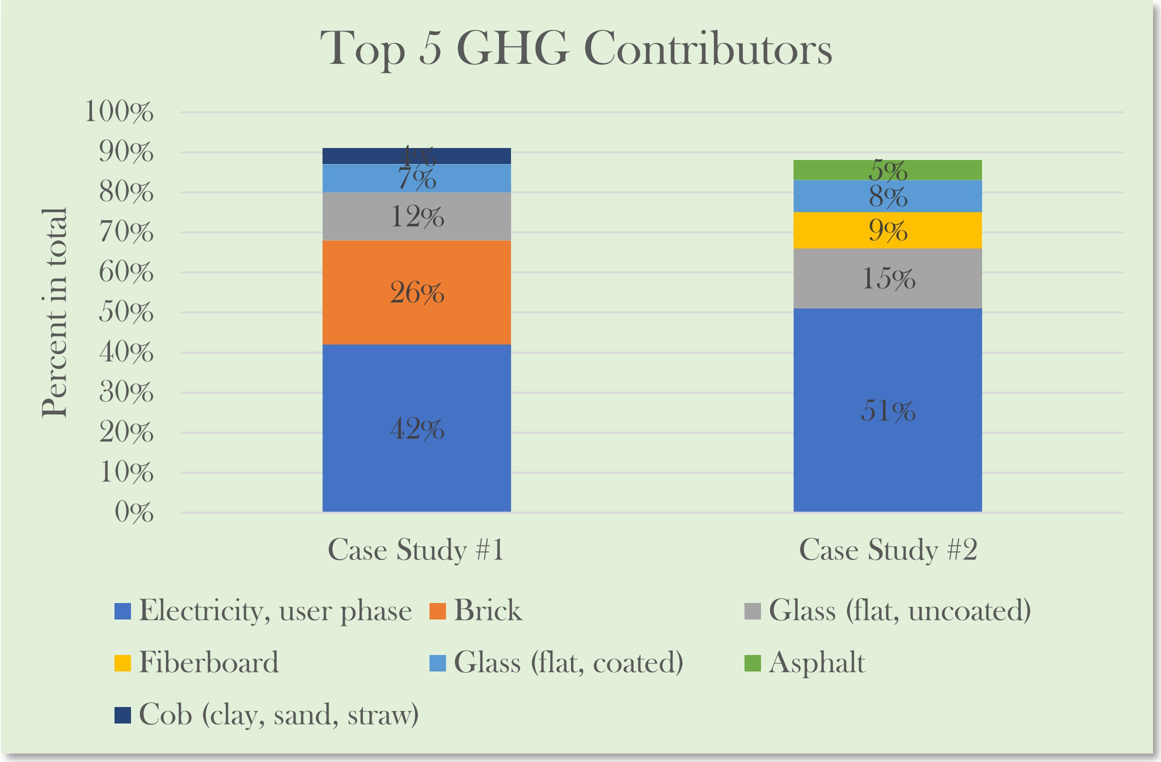

Figure 6: Case Study Result Comparison, Top 5 GHG Contributors.

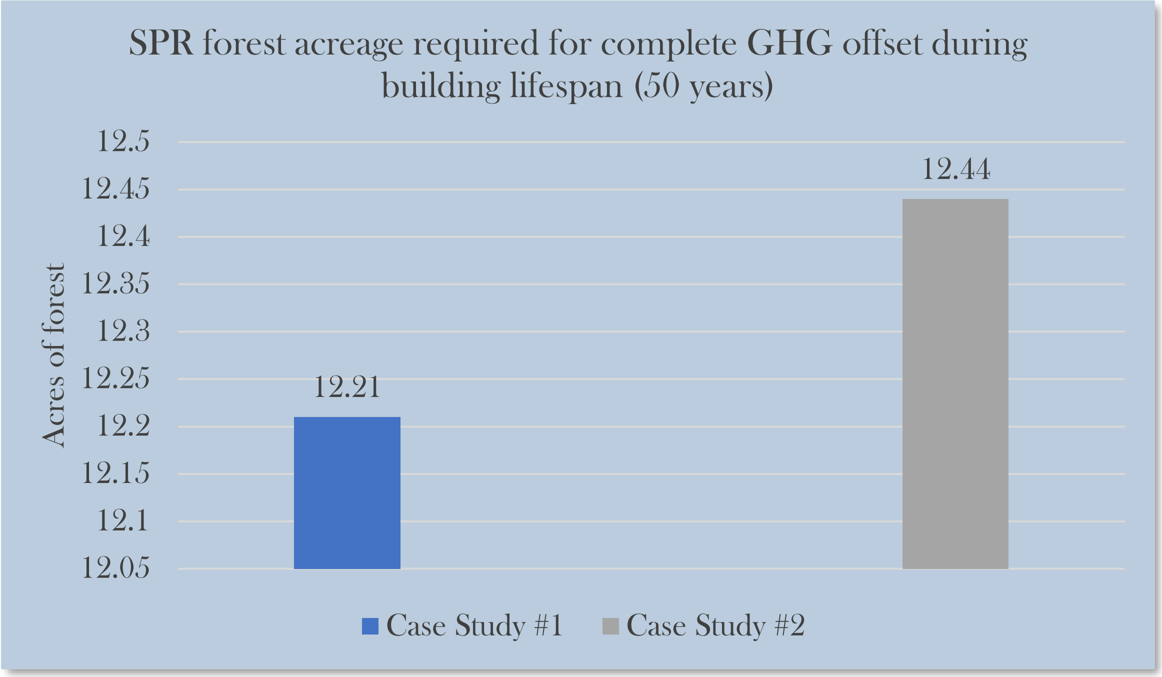

Figure 7: Case Study Result Comparison, forest acreage required for total GHG offset of buildings throughout a 50-year lifespan.

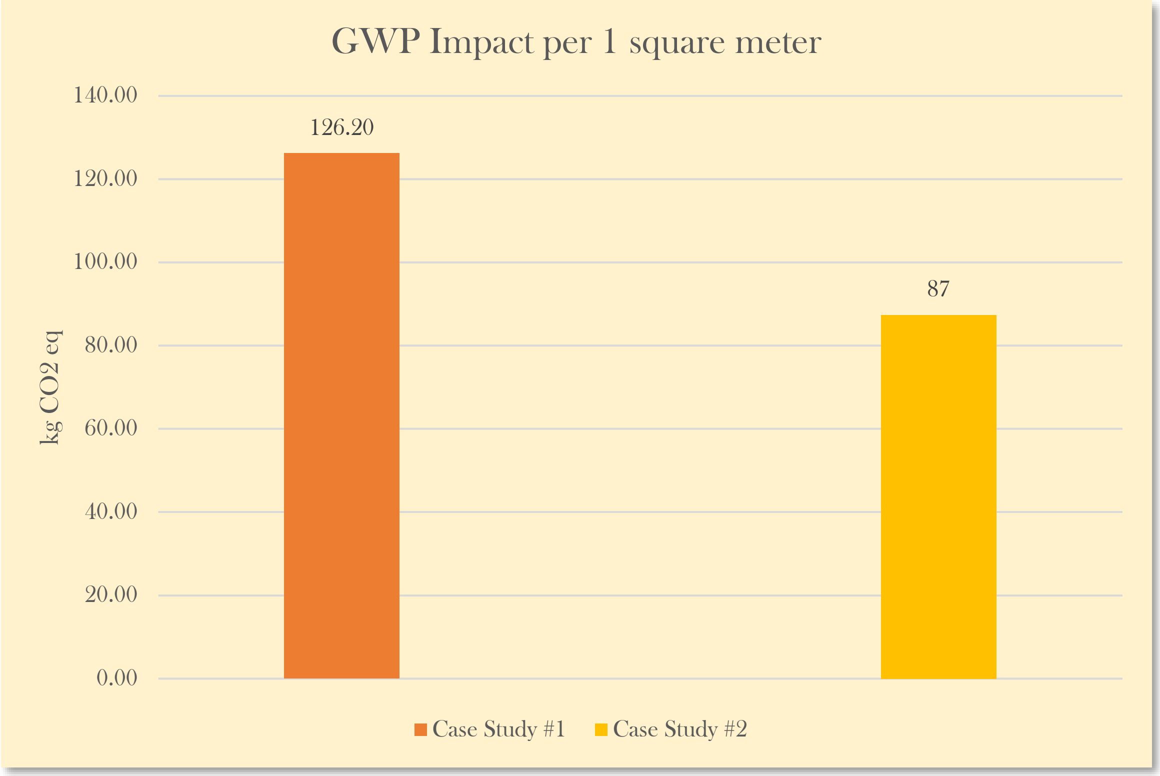

Figure 8: Case Study Comparison, Global Warming Potential impact per 1 square meter.

Chapter 5

DISCUSSION

5.1 EELCCP Interpretations

The EELCCP tool was structured to be transparent and user-friendly for individuals of all backgrounds. The data used for this tool was compared to existing LCIA studies to check for validity. For example, it was noted that the total electricity consumption for lighting and air conditioning is only half of what was stated in an Energy Information Administration (EIA) report (*Energy Information Administration*, 2022). The EELCCP records lighting and air conditioning as consuming 63.56 kWh/m^2 annually, while the 2022 EIA report states the annual national average lighting and air conditioning consumption for office and education buildings as 124 kWh/m^2. It is important to note, however, that most commercial buildings utilize ventilation in addition to air conditioning, which the EELCCP tool does not account for. This may account for the discrepancy in kWh between the tool and the EIA report. In future versions of the EELCCP, heating and ventilation should be included in addition to air conditioning, as well as the ability to customize projected air conditioning use throughout the year. Additionally, the EELCCP only accounts for light-emitting diode (LED) lightbulbs. One aspect of the tool that is highly valuable is its adaptability, meaning that in future iterations different types of lightbulbs can be included for a more thorough analysis.

The EELCCP tool has the ability to process 10 different impact categories, including acidification, carcinogenics, ecotoxicity, eutrophication, fossil fuel depletion, global warming, non-carcinogenics, ozone depletion, respiratory effects, and smog. For the purpose of this discussion, global warming is focused upon. As a form of data validation, the global warming impact analysis of concrete was compared to that of existing LCIA studies. The data utilized for the EELCCP tool has an impact analysis result of 205.15kg of CO_2 equivalent, which is about 50% lower than the LCIA study from Onyelowe, et al, which showed concrete as having 418.15 kg of CO_2 equivalent (Onyelowe et al., 2022).

5.2 Limitations of the EELCCP

As this is V1 of the EELCCP tool, there are a few limitations to be discussed. First, in the *User Input* tab, the "site preparation" data only takes into account excavation using a skid-steer loader and a hydraulic digger, and no other machine operations. Additionally, fuel consumption during construction is embedded into the machine operation data analysis, meaning that no additional fuels for transporting the machines to the project site are considered. On this note of transportation impacts, it is also important to acknowledge that the impact of transportation of construction materials was excluded from the EELCCP tool data. This information is not readily available during the project planning phase, so it was omitted by the author for V1. Based on relevant literature, it is estimated to take 102 liters of diesel to transport precast concrete to the construction site (Biswas, 2014). As this is a high volume of diesel for the transport of a single material, it would be valuable to include transportation values into impact analysis data in a future version of the EELCCP. An additional limitation of the EELCCP is that air conditioning power consumption was scaled up directly with the assumption that air conditioning is under operation 365 days a year. This assumption might not reflect the actual operational patterns of most buildings. For future versions of the EELCCP, it would be valuable to incorporate an option to choose the number of operational days a year for air conditioning, so as not to assume that it is in operation every day of the year. Additionally, it would be valuable to include ventilation and heating data in future versions of the tool, as these operations are pertinent to the successful operation of most large buildings.

5.3 Additions to the EELCCP

The most valuable part of the EELCCP is that it is flexible, and therefore expandable. Thanks to the implementation of the SPR Case Studies, some areas for improvement and addition to the EELCPP were uncovered. First, there is not a convenient way to compare multiple building scenarios side by side within the Excel format. The user has to either take screenshots of the inputs and results, or manually record these values on a piece of paper or a notes document. In future versions, a tab where users can easily compare different building scenarios would improve decision making abilities for users.

Additionally, the number of materials in the tool can be overwhelming when understanding the implications of your analysis results. In future versions, the EELCCP could benefit from a function to filter results so that only materials with inputted values are shown.

There are also a few units for materials choices that would be beneficial to update in the tool's database. For example, when researching typical ratios of materials for the case study scenarios, it was found that drywall is often measured in "sheets," wood for flooring or siding is often measured in "board feet," and bricks and tiles are often measured by the "number" of them. In the next version of the EELCCP, it would be easier for users to have these units of measurement to choose from in the dropdown menu along with the traditional volume and mass units that are already provided. Those updating the tool would need to conduct research to understand the volume or mass of a typical board foot, drywall sheet, etc. and program the *Unit Conversion* tab accordingly.

One major aspect of the EELCCP that can be improved upon in the next version would be the inclusion of a *Cost Calculation* tab. While some users may be convinced to use 'alternative' material choices simply based off LCI results, others may need cost tradeoff to better inform their decision making. Those updating the tool would need to perform desktop research to understand the average cost of each material by mass or volume, and subsequently code this information into the tool. Therefore, users would not only be able to understand the environmental impacts of their material choices, but the cost implications as well.

Chapter 6

CONCLUSION

It is imperative to understand the sustainability of a structure prior to its construction so that early design decisions can be made to reduce environmental impacts. NASA explains it best, "Global climate change is not a future problem. Changes to Earth's climate driven by increased human emissions of heat-trapping greenhouse gases are already having widespread effects on the environment. Effects that scientists had long predicted would result from global climate change are now occurring, such as sea ice loss, accelerated sea level rise, and longer, more intense heat waves" (Jackson, 2021).

The results of a changing climate are impacting the earth and its ecosystems now. As stewards of this planet, humans hold responsibility to reduce their carbon footprint as much and as quickly as possible. With the built environment contributing 40% of global CO_2 emissions annually, it is pertinent that carbon reduction be prioritized in this realm (*Architecture 2030*, 2021).

To better help architects and engineers make carbon smart design decisions, a variety of LCA-based tools have hit the market to assist in environmental impact metric reporting. However, there is a lack of an easy-to-interpret, early design tool that focuses on embodied carbon reduction through the use of LCD, with an emphasis on materials choice. Through the creation of V1 of the EELCCP, the construction sector is now provided with this exact tool. Utilizing SPR as a case study allowed the EELCCP to go through testing, with suggestions for its future improvement being recorded.

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APPENDICES

APPENDIX A

LCA Tool Comparison

Tool	**Overview**	**Data Analyzed (input)**	**Impact Categories (output)**	**Notes**
Athena Impact Estimator for Buildings	Downloadable software to compare the environmental implications of industrial, institutional, commercial, & residential new buildings or renovations.	• Material Manufacturing • Transportation • On-Site Construction • Regional Variation in Energy Use • Building type and assumed lifespan, maintenance, demolition and disposal	• GWP • Acidification • Human Health & Respiratory • Ozone Depletion • Photochemical Smog • Eutrophication • Fossil Fuel Consumption	• Requires LCA knowledge and skill to use this tool • No sustainability estimate for operational use
Building Life Cycle Cost Program	Downloadable software that compares the cost effectiveness	• The life cycle cost of two or more alternative designs	• Net Savings • Savings-to-Investment Ratio • Adjusted Internal Rate of Return	Not specific to materials; focuses more on cost

	of higher initial costs but lower operating costs (specifically for energy and water conservation and renewable energy)		Years to Payback	
One Click LCA Carbon Designer 3D	Purchased software that can generate and compare design options using ready-made building structures and materials	• Building design for baseline/template • Materials (type and amount)	• Carbon hotspots • Can look at different structural systems, assemblies, and specific products • Total carbon reductions or increases • Can look at building parts, material,	• Must buy a suite of LCA tools and book through the company for use • Requires LCA knowledge and skill to use this tool

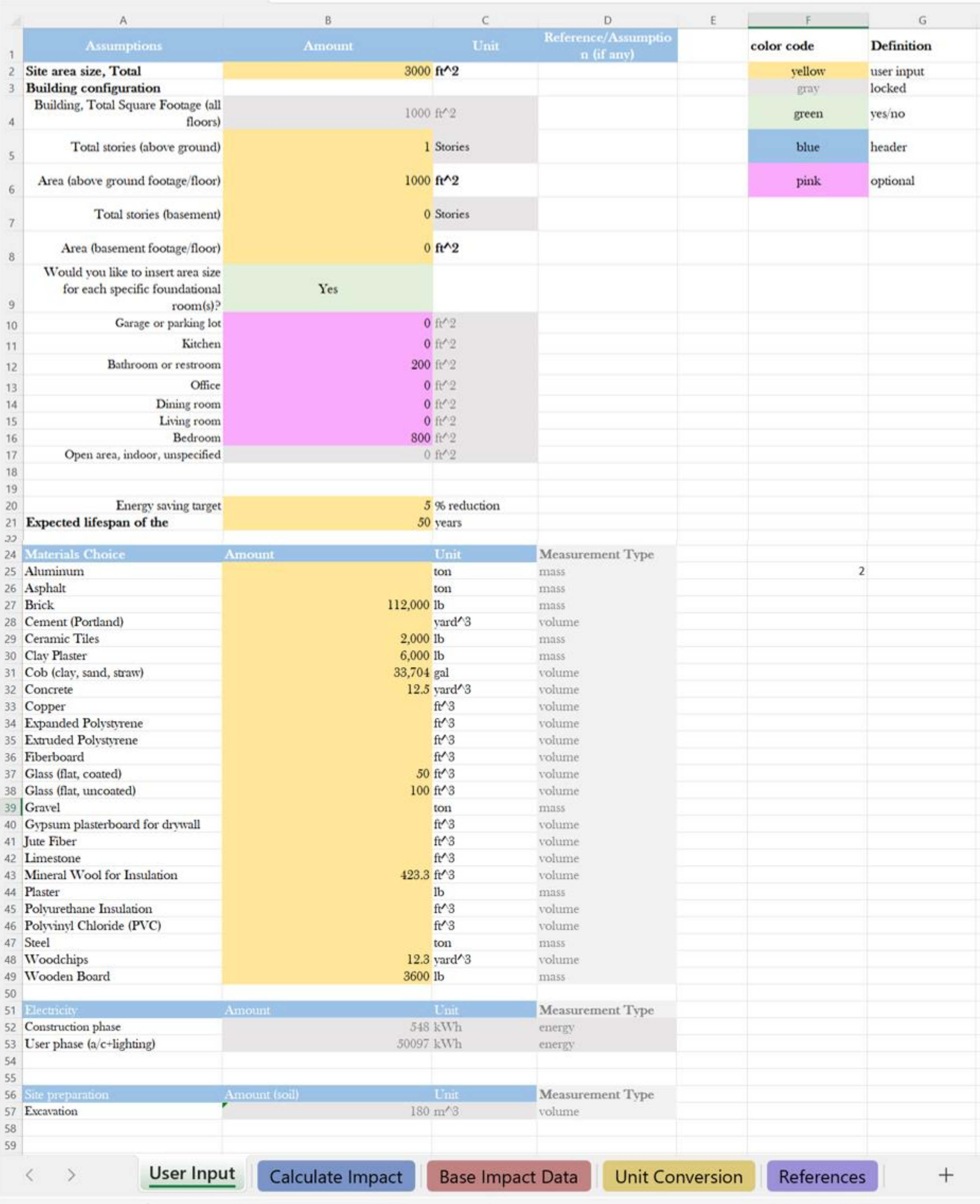
			classification, or component	
Tally	Downloadable software (free 10-day trial, then $700) that is compatible with Revit for whole-building analysis and analysis of design options. Accounts for cradle to grave LCA.	GaBi Data	• Cradle to Grave • Construction impacts and operational energy	• Requires LCA knowledge and skill to use this tool • High cost to download
Building Products Calculator	A Leadership in Energy and Environmental Design (LEED)	• Environmental product declarations • Sourcing of raw materials	• Total materials cost • Embodied carbon • Material ingredient	• Requires specific details, like manufacturer name,

	Environmental Product Declarations, Responsible Sourcing of Raw Materials, and Sustainable Credit for Material Ingredients excel-based calculator	• Material ingredients • Materials cost	reporting	description of product, and sustainable value criteria information to render results • Requires building details of *all* products being utilized in the design to render results • Must have an understanding of LEED standards to

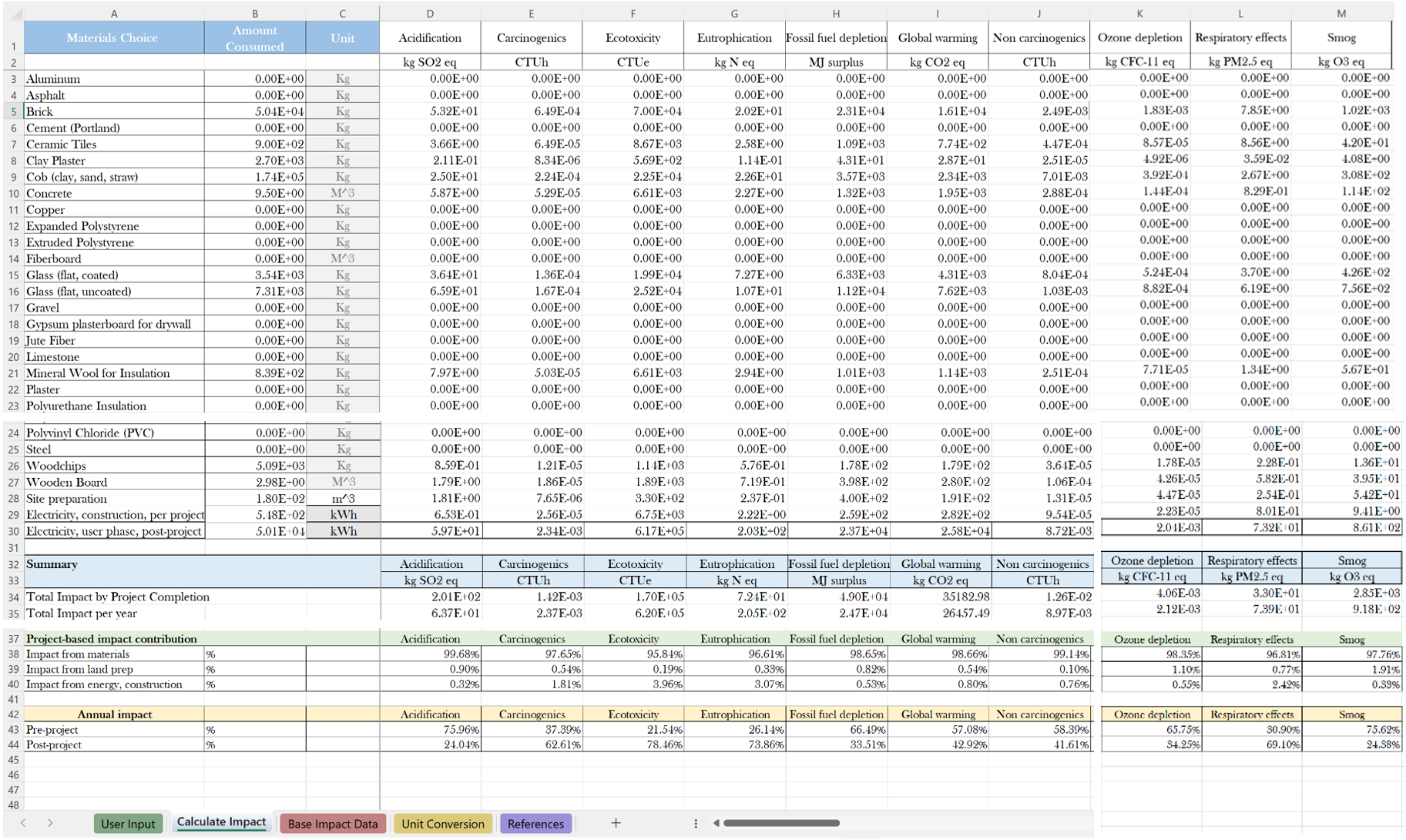
				utilize

APPENDIX B

Case Study #1: Student Housing, EELCCP Inputs & Results



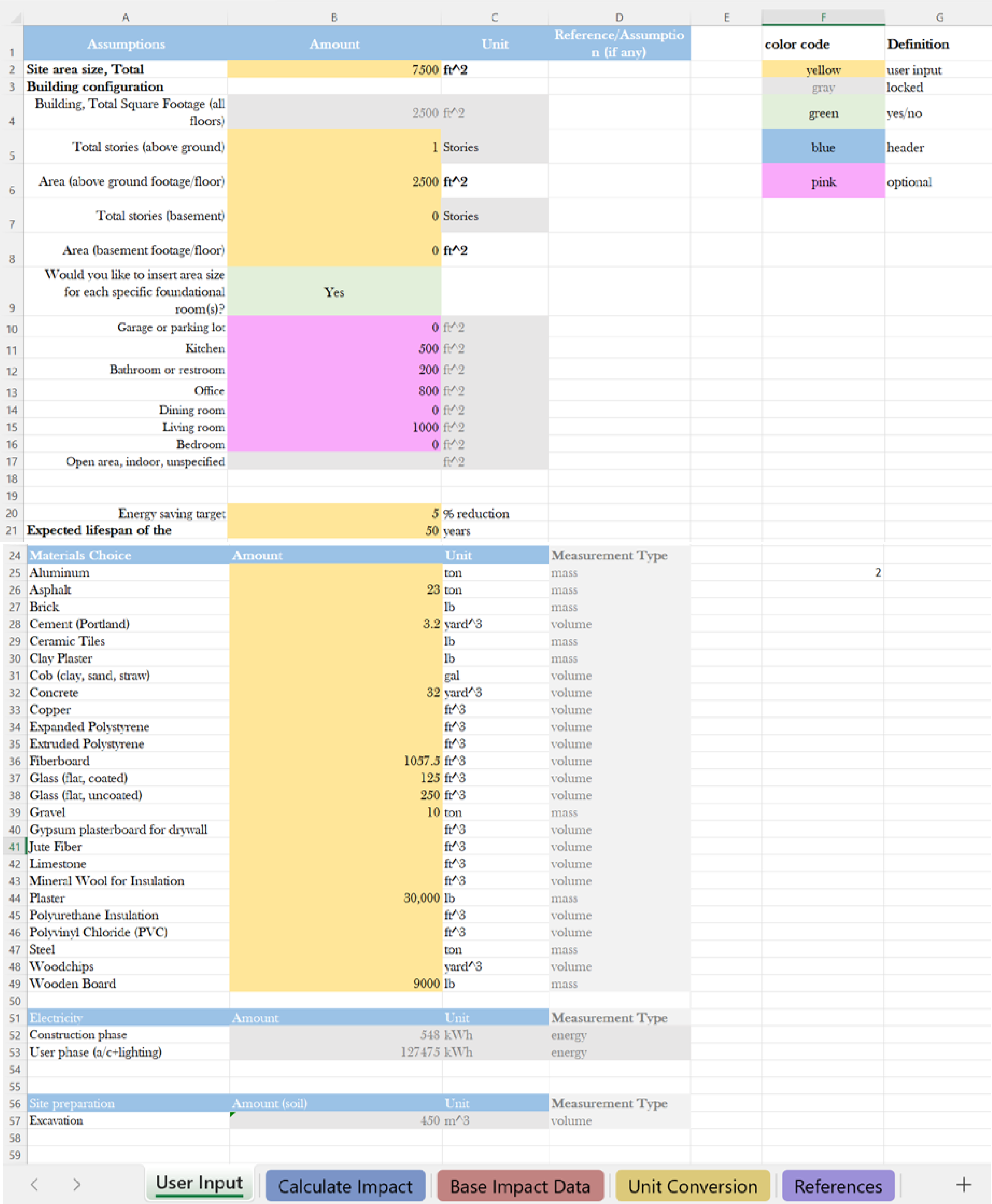
	A	B	C	D	E	F	G
1	Assumptions	Amount	Unit	Reference/Assumption (if any)		**color code**	**Definition**
2	**Site area size, Total**	3000	**ft^2**			yellow	user input
3	**Building configuration**					gray	locked
4	Building, Total Square Footage (all floors)	1000	ft^2			green	yes/no
5	Total stories (above ground)	1	Stories			blue	header
6	Area (above ground footage/floor)	1000	**ft^2**			pink	optional
7	Total stories (basement)	0	Stories				
8	Area (basement footage/floor)	0	**ft^2**				
9	Would you like to insert area size for each specific foundational room(s)?	Yes					
10	Garage or parking lot	0	ft^2				
11	Kitchen	0	ft^2				
12	Bathroom or restroom	200	ft^2				
13	Office	0	ft^2				
14	Dining room	0	ft^2				
15	Living room	0	ft^2				
16	Bedroom	800	ft^2				
17	Open area, indoor, unspecified	0	ft^2				
18							
19							
20	Energy saving target	5	% reduction				
21	**Expected lifespan of the**	50	years				
22							
24	Materials Choice	Amount	Unit	Measurement Type			
25	Aluminum		ton	mass		2	
26	Asphalt		ton	mass			
27	Brick	112,000	lb	mass			
28	Cement (Portland)		yard^3	volume			
29	Ceramic Tiles	2,000	lb	mass			
30	Clay Plaster	6,000	lb	mass			
31	Cob (clay, sand, straw)	33,704	gal	volume			
32	Concrete	12.5	yard^3	volume			
33	Copper		ft^3	volume			
34	Expanded Polystyrene		ft^3	volume			
35	Extruded Polystyrene		ft^3	volume			
36	Fiberboard		ft^3	volume			
37	Glass (flat, coated)	50	ft^3	volume			
38	Glass (flat, uncoated)	100	ft^3	volume			
39	Gravel		ton	mass			
40	Gypsum plasterboard for drywall		ft^3	volume			
41	Jute Fiber		ft^3	volume			
42	Limestone		ft^3	volume			
43	Mineral Wool for Insulation	423.3	ft^3	volume			
44	Plaster		lb	mass			
45	Polyurethane Insulation		ft^3	volume			
46	Polyvinyl Chloride (PVC)		ft^3	volume			
47	Steel		ton	mass			
48	Woodchips	12.3	yard^3	volume			
49	Wooden Board	3600	lb	mass			
50							
51	Electricity	Amount	Unit	Measurement Type			
52	Construction phase	548	kWh	energy			
53	User phase (a/c+lighting)	50097	kWh	energy			
54							
55							
56	Site preparation	Amount (soil)	Unit	Measurement Type			
57	Excavation	180	m^3	volume			
58							
59							



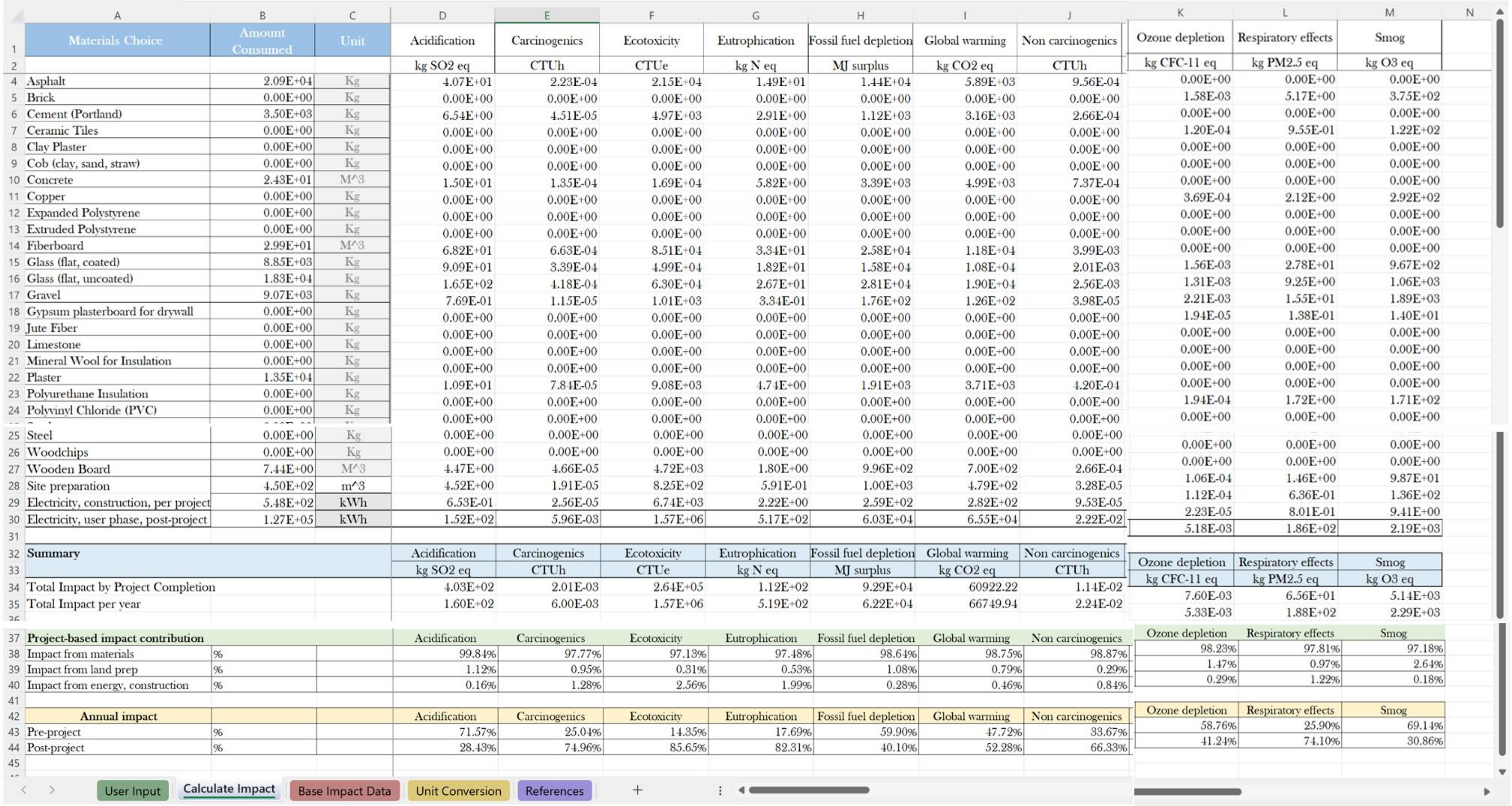
	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Materials Choice	Amount Consumed	Unit	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
2				kg SO2 eq	CTUh	CTUe	kg N eq	MJ surplus	kg CO2 eq	CTUh	kg CFC-11 eq	kg PM2.5 eq	kg O3 eq
3	Aluminum	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	Asphalt	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	Brick	5.04E+04	Kg	5.32E+01	6.49E-04	7.00E+04	2.02E+01	2.31E+04	1.61E+04	2.49E-03	1.83E-03	7.85E+00	1.02E+03
6	Cement (Portland)	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	Ceramic Tiles	9.00E+02	Kg	3.66E+00	6.49E-05	8.67E+03	2.58E+00	1.09E+03	7.74E+02	4.47E-04	8.57E-05	8.56E+00	4.20E+01
8	Clay Plaster	2.70E+03	Kg	2.11E-01	8.34E-06	5.69E+02	1.14E-01	4.31E+01	2.87E+01	2.51E-05	4.92E-06	3.59E-02	4.08E+00
9	Cob (clay, sand, straw)	1.74E+05	Kg	2.50E+01	2.24E-04	2.25E+04	2.26E+01	3.57E+03	2.34E+03	7.01E-03	3.92E-04	2.67E+00	3.08E+02
10	Concrete	9.50E+00	M^3	5.87E+00	5.29E-05	6.61E+03	2.27E+00	1.32E+03	1.95E+03	2.88E-04	1.44E-04	8.29E-01	1.14E+02
11	Copper	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	Expanded Polystyrene	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	Extruded Polystyrene	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	Fiberboard	0.00E+00	M^3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	Glass (flat, coated)	3.54E+03	Kg	3.64E+01	1.36E-04	1.99E+04	7.27E+00	6.33E+03	4.31E+03	8.04E-04	5.24E-04	3.70E+00	4.26E+02
16	Glass (flat, uncoated)	7.31E+03	Kg	6.59E+01	1.67E-04	2.52E+04	1.07E+01	1.12E+04	7.62E+03	1.03E-03	8.82E-04	6.19E+00	7.56E+02
17	Gravel	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18	Gypsum plasterboard for drywall	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
19	Jute Fiber	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
20	Limestone	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21	Mineral Wool for Insulation	8.39E+02	Kg	7.97E+00	5.03E-05	6.61E+03	2.94E+00	1.01E+03	1.14E+03	2.51E-04	7.71E-05	1.34E+00	5.67E+01
22	Plaster	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
23	Polyurethane Insulation	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
24	Polyvinyl Chloride (PVC)	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
25	Steel	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
26	Woodchips	5.09E+03	Kg	8.59E-01	1.21E-05	1.14E+03	5.76E-01	1.78E+02	1.79E+02	3.64E-05	1.78E-05	2.28E-01	1.36E+01
27	Wooden Board	2.98E+00	M^3	1.79E+00	1.86E-05	1.89E+03	7.19E-01	3.98E+02	2.80E+02	1.06E-04	4.26E-05	5.82E-01	3.95E+01
28	Site preparation	1.80E+02	m^3	1.81E+00	7.65E-06	3.30E+02	2.37E-01	4.00E+02	1.91E+02	1.31E-05	4.47E-05	2.54E-01	5.42E+01
29	Electricity, construction, per project	5.48E+02	kWh	6.53E-01	2.56E-05	6.75E+03	2.22E+00	2.59E+02	2.82E+02	9.54E-05	2.23E-05	8.01E-01	9.41E+00
30	Electricity, user phase, post-project	5.01E+04	kWh	5.97E+01	2.34E-03	6.17E+05	2.03E+02	2.37E+04	2.58E+04	8.72E-03	2.04E-03	7.32E+01	8.61E+02
31													
32	**Summary**			Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
33				kg SO2 eq	CTUh	CTUe	kg N eq	MJ surplus	kg CO2 eq	CTUh	kg CFC-11 eq	kg PM2.5 eq	kg O3 eq
34	Total Impact by Project Completion			2.01E+02	1.42E-03	1.70E+05	7.24E+01	4.90E+04	35182.98	1.26E-02	4.06E-03	3.30E+01	2.85E+03
35	Total Impact per year			6.37E+01	2.37E-03	6.20E+05	2.05E+02	2.47E+04	26457.49	8.97E-03	2.12E-03	7.39E+01	9.18E+02
37	**Project-based impact contribution**			Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
38	Impact from materials	%		99.68%	97.65%	95.84%	96.61%	98.65%	98.66%	99.14%	98.35%	96.81%	97.76%
39	Impact from land prep	%		0.90%	0.54%	0.19%	0.33%	0.82%	0.54%	0.10%	1.10%	0.77%	1.91%
40	Impact from energy, construction	%		0.32%	1.81%	3.96%	3.07%	0.53%	0.80%	0.76%	0.55%	2.42%	0.33%
41													
42	**Annual impact**			Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
43	Pre-project	%		75.96%	37.39%	21.54%	26.14%	66.49%	57.08%	58.39%	65.75%	30.90%	75.62%
44	Post-project	%		24.04%	62.61%	78.46%	73.86%	33.51%	42.92%	41.61%	34.25%	69.10%	24.38%
45													
46													
47													
48													

APPENDIX C

Case Study #2: Multipurpose Space, EELCCP Inputs & Results



	A	B	C	D	E	F	G
1	Assumptions	Amount	Unit	Reference/Assumption (if any)		**color code**	**Definition**
2	**Site area size, Total**	7500	**ft^2**			yellow	user input
3	**Building configuration**					gray	locked
4	Building, Total Square Footage (all floors)	2500	ft^2			green	yes/no
5	Total stories (above ground)	1	Stories			blue	header
6	Area (above ground footage/floor)	2500	**ft^2**			pink	optional
7	Total stories (basement)	0	Stories				
8	Area (basement footage/floor)	0	**ft^2**				
9	Would you like to insert area size for each specific foundational room(s)?	Yes					
10	Garage or parking lot	0	ft^2				
11	Kitchen	500	ft^2				
12	Bathroom or restroom	200	ft^2				
13	Office	800	ft^2				
14	Dining room	0	ft^2				
15	Living room	1000	ft^2				
16	Bedroom	0	ft^2				
17	Open area, indoor, unspecified		ft^2				
18							
19							
20	Energy saving target	*5*	% reduction				
21	**Expected lifespan of the**	*50*	years				
24	Materials Choice	Amount	Unit	Measurement Type			
25	Aluminum		ton	mass		2	
26	Asphalt	23	ton	mass			
27	Brick		lb	mass			
28	Cement (Portland)	3.2	yard^3	volume			
29	Ceramic Tiles		lb	mass			
30	Clay Plaster		lb	mass			
31	Cob (clay, sand, straw)		gal	volume			
32	Concrete	32	yard^3	volume			
33	Copper		ft^3	volume			
34	Expanded Polystyrene		ft^3	volume			
35	Extruded Polystyrene		ft^3	volume			
36	Fiberboard	1057.5	ft^3	volume			
37	Glass (flat, coated)	125	ft^3	volume			
38	Glass (flat, uncoated)	250	ft^3	volume			
39	Gravel	10	ton	mass			
40	Gypsum plasterboard for drywall		ft^3	volume			
41	Jute Fiber		ft^3	volume			
42	Limestone		ft^3	volume			
43	Mineral Wool for Insulation		ft^3	volume			
44	Plaster	30,000	lb	mass			
45	Polyurethane Insulation		ft^3	volume			
46	Polyvinyl Chloride (PVC)		ft^3	volume			
47	Steel		ton	mass			
48	Woodchips		yard^3	volume			
49	Wooden Board	9000	lb	mass			
50							
51	Electricity	Amount	Unit	Measurement Type			
52	Construction phase	548	kWh	energy			
53	User phase (a/c+lighting)	127475	kWh	energy			
54							
55							
56	Site preparation	Amount (soil)	Unit	Measurement Type			
57	Excavation	450	m^3	volume			
58							
59							



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Materials Choice	Amount Consumed	Unit	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
2				kg SO2 eq	CTUh	CTUe	kg N eq	MJ surplus	kg CO2 eq	CTUh	kg CFC-11 eq	kg PM2.5 eq	kg O3 eq
4	Asphalt	2.09E+04	Kg	4.07E+01	2.23E-04	2.15E+04	1.49E+01	1.44E+04	5.89E+03	9.56E-04	0.00E+00	0.00E+00	0.00E+00
5	Brick	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.58E-03	5.17E+00	3.75E+02
6	Cement (Portland)	3.50E+03	Kg	6.54E+00	4.51E-05	4.97E+03	2.91E+00	1.12E+03	3.16E+03	2.66E-04	0.00E+00	0.00E+00	0.00E+00
7	Ceramic Tiles	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.20E-04	9.55E-01	1.22E+02
8	Clay Plaster	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	Cob (clay, sand, straw)	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	Concrete	2.43E+01	M^3	1.50E+01	1.35E-04	1.69E+04	5.82E+00	3.39E+03	4.99E+03	7.37E-04	0.00E+00	0.00E+00	0.00E+00
11	Copper	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.69E-04	2.12E+00	2.92E+02
12	Expanded Polystyrene	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	Extruded Polystyrene	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	Fiberboard	2.99E+01	M^3	6.82E+01	6.63E-04	8.51E+04	3.34E+01	2.58E+04	1.18E+04	3.99E-03	0.00E+00	0.00E+00	0.00E+00
15	Glass (flat, coated)	8.85E+03	Kg	9.09E+01	3.39E-04	4.99E+04	1.82E+01	1.58E+04	1.08E+04	2.01E-03	1.56E-03	2.78E+01	9.67E+02
16	Glass (flat, uncoated)	1.83E+04	Kg	1.65E+02	4.18E-04	6.30E+04	2.67E+01	2.81E+04	1.90E+04	2.56E-03	1.31E-03	9.25E+00	1.06E+03
17	Gravel	9.07E+03	Kg	7.69E-01	1.15E-05	1.01E+03	3.34E-01	1.76E+02	1.26E+02	3.98E-05	2.21E-03	1.55E+01	1.89E+03
18	Gypsum plasterboard for drywall	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.94E-05	1.38E-01	1.40E+01
19	Jute Fiber	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
20	Limestone	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21	Mineral Wool for Insulation	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
22	Plaster	1.35E+04	Kg	1.09E+01	7.84E-05	9.08E+03	4.74E+00	1.91E+03	3.71E+03	4.20E-04	0.00E+00	0.00E+00	0.00E+00
23	Polyurethane Insulation	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.94E-04	1.72E+00	1.71E+02
24	Polyvinyl Chloride (PVC)	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
25	Steel	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
26	Woodchips	0.00E+00	Kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
27	Wooden Board	7.44E+00	M^3	4.47E+00	4.66E-05	4.72E+03	1.80E+00	9.96E+02	7.00E+02	2.66E-04	1.06E-04	1.46E+00	9.87E+01
28	Site preparation	4.50E+02	m^3	4.52E+00	1.91E-05	8.25E+02	5.91E-01	1.00E+03	4.79E+02	3.28E-05	1.12E-04	6.36E-01	1.36E+02
29	Electricity, construction, per project	5.48E+02	kWh	6.53E-01	2.56E-05	6.74E+03	2.22E+00	2.59E+02	2.82E+02	9.53E-05	2.23E-05	8.01E-01	9.41E+00
30	Electricity, user phase, post-project	1.27E+05	kWh	1.52E+02	5.96E-03	1.57E+06	5.17E+02	6.03E+04	6.55E+04	2.22E-02	5.18E-03	1.86E+02	2.19E+03

		Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
32	**Summary**										
33		kg SO2 eq	CTUh	CTUe	kg N eq	MJ surplus	kg CO2 eq	CTUh	kg CFC-11 eq	kg PM2.5 eq	kg O3 eq
34	Total Impact by Project Completion	4.03E+02	2.01E-03	2.64E+05	1.12E+02	9.29E+04	60922.22	1.14E-02	7.60E-03	6.56E+01	5.14E+03
35	Total Impact per year	1.60E+02	6.00E-03	1.57E+06	5.19E+02	6.22E+04	66749.94	2.24E-02	5.33E-03	1.88E+02	2.29E+03

37	**Project-based impact contribution**		Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
38	Impact from materials	%	99.84%	97.77%	97.13%	97.48%	98.64%	98.75%	98.87%	98.23%	97.81%	97.18%
39	Impact from land prep	%	1.12%	0.95%	0.31%	0.53%	1.08%	0.79%	0.29%	1.47%	0.97%	2.64%
40	Impact from energy, construction	%	0.16%	1.28%	2.56%	1.99%	0.28%	0.46%	0.84%	0.29%	1.22%	0.18%

42	**Annual impact**		Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil fuel depletion	Global warming	Non carcinogenics	Ozone depletion	Respiratory effects	Smog
43	Pre-project	%	71.57%	25.04%	14.35%	17.69%	59.90%	47.72%	33.67%	58.76%	25.90%	69.14%
44	Post-project	%	28.43%	74.96%	85.65%	82.31%	40.10%	52.28%	66.33%	41.24%	74.10%	30.86%