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Comparison of Reinforced Concrete Bridge and Fiber Reinforced Polymer Bridge Using Life Cycle Assessment

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UNIVERSITY OF MIAMI

COMPARISON OF REINFORCED CONCRETE BRIDGE AND FIBER REINFORCED POLYMER BRIDGE USING LIFE CYCLE ASSESSMENT

By

Ezgi Ozcoban

A THESIS

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Comparison of Reinforced Concrete Bridge
and Fiber Reinforced Polymer Bridge
Using Life Cycle Assessment

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Life Cycle Assessment (LCA) is an important tool assessing environmental impacts of the entire life cycle of a product or service. It provides an alternative method to enable reducing carbon emission and embodied energy. The purpose of this study is to use LCA to compare two different structural materials used as reinforcement in a concrete bridge. The two materials are conventional steel reinforcement and Fiber Reinforced Polymer (FRP). The results show that FRP reinforced bridge produces 50% less carbon dioxide and 59% Embodied Energy throughout all the stages of LCA based on predicted equal life-span of two bridge applications.

Key Words: Life Cycle Assessment, Fiber Reinforced Polymer, Carbon Emission, Embodied Energy.

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Chapter 1

Introduction

Human activities substantially contribute to global warming by increasing the emission of greenhouse gases (GHG). GHG are emitted by burning coal, natural gas and oil to produce electricity which is used for industrial activities and heating purposes in buildings (IPCC 2009).GHG trap the heat in the atmosphere and cause an increase in earth's temperature. Carbon dioxide (CO_2) is one of the main GHG that has higher atmospheric concentration. Overall CO_2 emissions increased by 8.6% from 1990 to 2014 in U.S. Global emissions of GHG are categorized into five economic sectors such as electricity, industry, transportation, building and agriculture. The industrial sector accounts for 21% of U.S. GHG emissions in 2014 (E. P. Agency 2016).The environmental Protection Agency publishes an annual report is called *the Inventory of U.S. Greenhouse Gas Emissions and Sinks*. In chapter 4, Industrial Processes and Product Use (IPPU) presents GHG data emitted from industrial processes such as different material production. (E. P. Agency 2016). The proper selection of construction materials can lead to significant reduction of GHG emissions during the construction phase of buildings (Marıˊa Jesuˊ s Gonzaˊ lez 2005).

Material usage is a key factor in the construction industry, contributing to all stages of the construction process that has significant environmental impacts (EI), starting from the extraction of raw materials to the ends of product's life. Material production results in large amounts of carbon emission and embodied energy (EE). Seeking alternative building materials can reduce these impacts. To carry out this goal, alternative materials must be examined as the first step of product design in terms of both architectural and engineering aspects. To incorporate material selection into the design decision process, finding alternate solution has a significant impact on reducing EE originated during product life cycle period. Substitute material might have higher carbon dioxide and EE per unit but to decrease the amount of material used in the project leads to overall reduction in EI. On the other hand, looking for new, sustainable, eco-friendly materials has been initiative factor to be able to build more affordable constructions. Despite material selection methods reduction of EI, it is being considered not cost effective by majority of construction companies. However, it is controversial that selection of cost efficient construction materials sometimes cannot contribute sustainable designs, reduce carbon emission and EE.

Material durability is one of the factors that leads to decrease EI. It needs to be considered while selecting materials for the structure. Durability extends the life span of the structure and that makes the structure more sustainable and induces less EI (Mir M. Ali 2010). Structures made from materials that lead to an increase in the project life cycle will not need to be demolished at the same time as structures, made from less durable materials.

The construction sector has been searching for alternative sustainable materials due to increasing resources consumption. Therefore, there are plenty of projects that were built with alternate materials that contribute to environmental friendly projects. West Mill Bridge in the United Kingdom is one of the significant examples that uses alternative material implementation. Traditionally, steel and concrete are the foremost materials that structurally apply to bridge construction. However, due to their negative long standing impacts, such as corrosion and maintenance, new alternative solutions have been considered in construction field. Fiber reinforced Polymer (FRP) is one of the innovative technologies that has been applied since late 1980s for construction projects (Lijuan Cheng 2006).

West Mill Bridge is one of these applications and it is considered as the first bridge in Europe, made entirely out of FRP in 2002. The need for reducing maintenance, EI and increasing life span of the infrastructure is the reason behind these new materials and applications. West Mill Bridge is constructed with a FRP deck, beams and side paneling whose span is 10m and 6.8m wide. The result of this innovative application indicates that the installation time is decreased and the less maintenance is needed compared to conventional structures (Täljsten 2007).

Chapter 2

Life Cycle Assessment Principles and Framework

2.1 Methodology and Tools

LCA is a method that combines a broad quantitative understanding of potential EI on products, and services. LCA is associated with cradle-to-grave approach, which assesses all EI of a product's life starting from extraction of the raw materials and ending with where the materials go once the product's useful life is over. Due to the fact that resource consumption has been increasing, researches have been improved to find alternative solutions, materials and different ways of production to bring under control the growing resource consumption and the their EI.

The Origin of studying EI is date back to 1960s. One of the first studies was carried out and funded by Coca Cola Company to establish environmental affect discharged from beverage containers (Guinée 2010). Another investigation was conducted in United Kingdom regarding beverage containers made from a variety of materials such as plastic, glass, steel and aluminum to differentiate their characteristic features and potential environmental hazard release from different materials. (E. E. Agency 1997). Experiments helped to discover alternative sources for the products that release less carbon dioxide and have lower EE. In the 1990s, LCA became a standardized, decision-making tool and started to serve a wide range of industries as the solution based methodology that gives a clear understanding of EI of the products and services.

The International Organization describes LCA framework and principles for standardization in ISO 14040 (ISO 2006). ISO 14040 contains four main stages; definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase and the life cycle interpretation phase, reporting and critical review of the LCA as illustrated in Figure 1. First stage, which is Goal and Scope Definition, identifies boundaries and objectives of the intended study. A functional unit, which determines and quantifies a product's properties in the system is specified under the definition of scope.

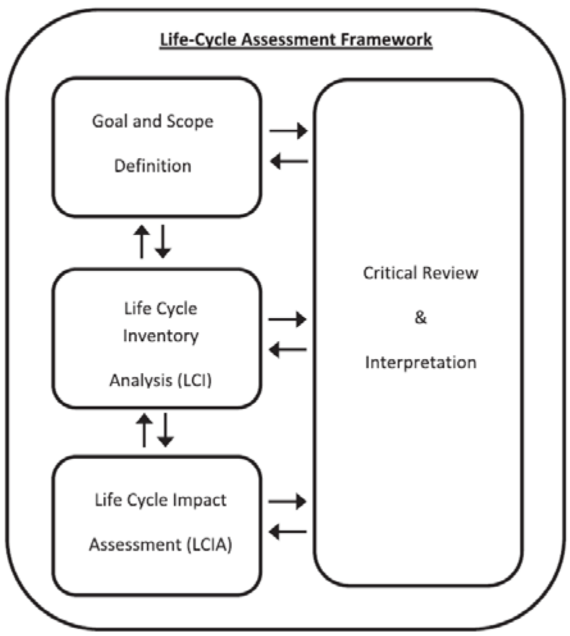

Figure 1 Framework for LCA (ISO 14040:2006)

The LCI stage evaluates inputs and outputs associated with product, and quantifies data the inventory of data. LCIA phase covers four main categories, which is classification, characterization, and weighting and interprets outputs provided from LCI phase to identify environmental issues (Rolf Frischknecht 1998). Last phase is Critical Review and

Interpretation which indicates data obtained from LCA and LCI stages and accounts for finalize implemented study.

This paper will provide extensive accurate data, and detailed material qualification for the described stages of LCA and LCI. The Inventory of Carbon Energy Version 1.6a (Hammond 2008) is used along with RS Means Building Construction Data which is used to determine types of equipment for deconstruction process (Means 2016). Environmental Protection Agency's *Motor Vehicle Emission Simulator* (U.S. EPA MOVES (2010b) 2010) to estimate emissions for the transportation of the materials and site equipment and Eco Impact Calculator Tool (Association n.d.) to calculate EI of Fiber Reinforced Polymer.

2.2 Goal and Scope Definition

2.2.1 Goal of the Study

Raising awareness of increasing EI of the construction sector leads to the studies that apply LCA to structures, which contribute precise results and provide opportunities to evaluate compare the EI of structural systems. The aim of intended study is to analyze the environmental effects of two different structural systems applied to the same pedestrian bridge and to determine and compare the EI of these two applications.

2.2.2 Scope of the Study

The project called "Innovation Bridge" is located in University of Miami Campus. It connects a sports facility to the communal area for pedestrian access. The bridge construction started in November 2015 and was completed in May 2016. The study will analyze the Innovation Bridge using two different reinforcement materials, steel and FRP reinforcements. Research was funded by UTC Center on Research on Concrete Applications for Sustainable Transportation (RE-CAST), NSF Industry/University Cooperative Research Center for the Integration of Composites into Infrastructure (CICI), Infravation Project Sustainable Concrete Using Seawater, Salt-Contaminated Aggregates and Non-Corrosive Reinforcement (SECON) and Principal Investigator was Antonio Nanni.

2.3 Functional Unit

A functional unit (FU), which is described as a tool to relate inputs and outputs providing by the selected system in ISO 14040. It serves for a function in the studied system. For the comparative studies, it is required to have same FU for each system (Bo Weidema 2004).

In this paper, there are two FU's, one for each type of bridge. Functional Unit 1 (FU-1) is a steel-reinforced concrete bridge and Functional Unit 2 (FU-2) is a bridge with Fiber Reinforced Polymer (FRP) reinforcement. The reason behind determining whole bridge structure as functional unit is that the functional unit serves the same function. Therefore, it might not give definitive results if only a particular section of the bridge is selected to analyze due to the inconsistent distribution of determined materials throughout the system.

Chapter 3

Structural Systems and Material Selection Scenario

3.1 Traditional Steel-Reinforced Concrete Bridges

Among the bridge structural design strategies, steel reinforced concrete bridges that are commonly used all around the world. However, material selection is based on environmental quality of the site, design criteria, material accessibility and life cycle cost (Horvath and Hendrickson). Since the concrete is a brittle material by itself, it is strengthened by adding steel reinforcement to resist the tension forces. The result of the study comparing steel bridge and steel-reinforced concrete bridge using equivalent design shows that steel-reinforced concrete bridge has lower EI. (Arpad Horvath 1998). This brings attention to the usage of reinforced concrete to reduce the EI of bridge construction and to further reduce the EI of reinforced concrete bridges.

One of the drawbacks of using this traditional steel reinforcement method is corrosion. The concrete provides protection for steel bar and prevents it from existing climate condition during presence of high alkalinity (Ahmad 2002). By the time, due to the interaction of chloride or deicing chemicals coming from severe environment reaches to reinforcement embedded in concrete and cause corrosion (Banu Dragos 2010). The untimely corrosion of reinforcement occurs in bridge structures has led to deterioration before their expected life span in United States (Dale P. Bentz 2014). There are different measures that causes corrosion. Due to temperature variation and increasing use of deicing salt is indicated as significant factor that has led to corrosion and a decrease in life expectancy of reinforced concrete structures (Craig R. Michaluk 1998). Another study has been carried out for concrete building structures in Arabian Gulf Region which has severe weather condition as hot climate, cold climate and salty environment, is called macro and micro climate. Concrete samples that were taken from the structures to determine the impact of salt and hot weather on the concrete. They were analyzed and results showed that a high intensity of salt and hot weather conditions are considerable impacts that cause corrosion. (Zein-Alabideen 2001). Corrosion requires additional maintenance operations such as rehabilitation and traffic disruption (Thompson 2003). Further, there might be a remarkable increase in expected life cycle cost of the system due to a decrease in the life span.

3.2 Fiber Reinforced Polymer (FRP) and Applications

With increasing awareness of environmental issues, alternative solutions have been applied for the construction field. FRP which is a composite material strengthened with fibers. That has been used for products in many industrial applications. FRP is commonly applied for replacement of existing deteriorated structures because of its lightweight and strength. FRP decks have become an option for new bridge constructions and refurbishment (Valbona Mara 2013).

The deck is considered a critical component of the structure that utilizes composite materials. Besides the usage of FRP as an entire deck structure, FRP has been also used as reinforcement in composite systems. The fibers that strengthen FRP consists of Glass-fiber Reinforced Polymer (GFRP), Carbon-fiber Reinforced Polymer (CFRP) and Basalt-fiber Reinforced Polymer (BFRP). It is also considered a cost-effective strategy to combine conventional concrete with high strength capacity composite materials (FRP) (Lijuan

Cheng 2006). FRP bars are an alternative and practical structural material for concrete structures and have many advantages, such as non-corrosive and lightweight properties.

Sustainable aspect is one of the measurements that needs to be considered during the selection of proper alternative material for the structures. Reducing the energy consumption, emissions to water, air and soil, waste generation and virgin material usage leads to decrease of infrastructure EI throughout their life-cycle (Valbona Mara 2013). One of the researches that focuses on EI of possible material choices, compared different structural materials for the footbridge that was planned to build in Netherlands. EI were analyzed under three main indicators, energy consumption, pollution to the air and pollution to the water. Results showed that FRP bridge has lower EI compared to bridges used structural steel, stainless steel, aluminum and reinforced steel (Daniel 2010).

When it comes to finding alternative solutions for the construction industry, projects' EI need to account for energy consumption and carbon emission. The first stage of life-cycle assessment accounts for the material processing and is a primary part of energy consumption. While assessing energy consumption, a material's quantity and EI are the key information that need to be provided. An energy consumption study was done by comparing the different materials on bridge construction by BECO group. In the study, GFRP and CFRP composites were used in the superstructure of 12-meter Road Bridge and they were replaced by steel and concrete to compare their energy consumption of different materials on the same application. Four different materials used in same bridge design, results showed that the bridge superstructure that was made with GFRP contains the lowest energy consumption, which is equivalent to 700 MJ. This example shows that using composite materials can lead to energy saving due to using less material as compared to concrete (Valbona Mara 2013).

The advantages and disadvantages of using FRP material in the construction field depends on the design approach, structural properties and the size of the project. One of the advantages of FRP applications is to provide longer service life with less maintenance compared to other materials (Theresa A. Hoffard 2005). Due to its lightweight, it is easy to install and can be fabricated and easy to transport to construction site. That leads to less EE in the transportation of the materials. It is shown that carbon emission of FRP can be less than is required for precast concrete bridge carbon emission (Hirokazu Tanaka 2006). Potential disadvantages of FRP that needs to be considered are its initial cost, unit carbon emission and EE. Since FRP is a relatively new material, more research is needed to understand its service life, long-term carbon emission impact and EE.

Chapter 4

Steel-Reinforced Bridge (FU-1)

FU-1 was designed for use at the University of Miami campus to serve as pedestrian bridge. The same design approach and requirements were used when designing FU-2, which is reinforced with FRP. The number, type and spacing of reinforcements are different in FRP bridge. Design dimension of main concrete elements forming the bridge, back walls, curbs, side blocks and deck stayed the same. Following five figures demonstrates the structural comparison of these two bridge designs. As it is shown in Figure 2 with red marking. The C-shaped steel reinforcements in the side block of the pile cap are No. 5 at 10 in. (25.4cm) o.c. C-shaped steel reinforcement are used. No. 4 at 8 in. (203mm) o.c. U-shaped steel reinforcements are used to splice curb to side blocks in the transverse direction as mark with blue color in Figure 2.

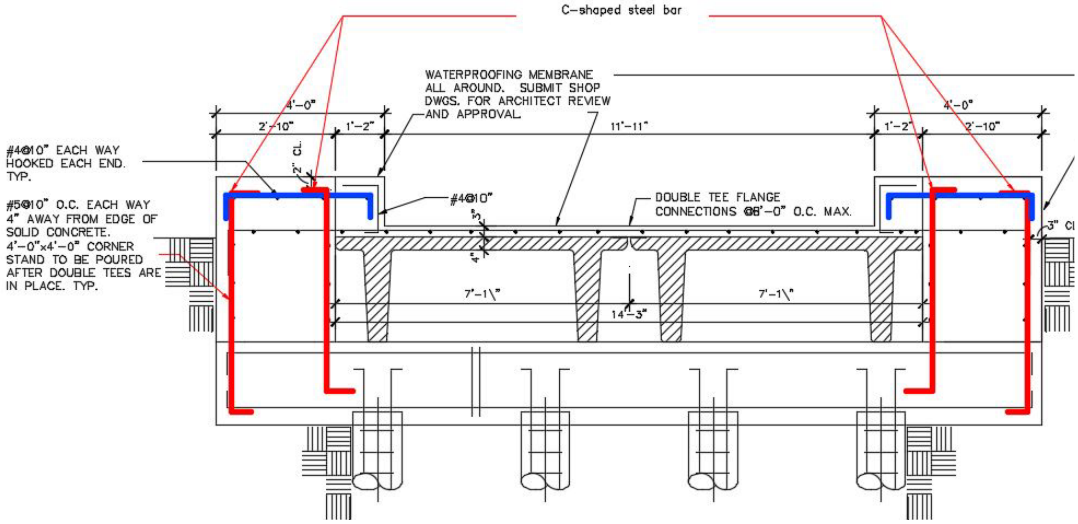

Figure 2: Cross Section at FU-1 Pile Cap

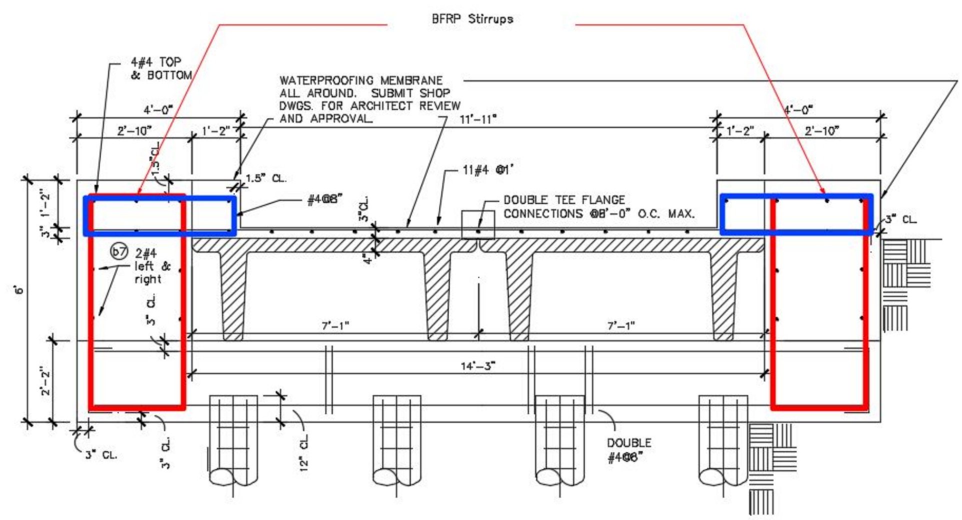

Figure 3: Cross Section at FU-2 Pile Cap

Figure 4 and Figure 5 are taken from longitudinal direction of the bridges to illustrate the difference between the double ties at pile caps between FU-1 and FU-2. The steel-reinforced bridge consists of eight auger-cast piles. However, diameter and height of piles differ from FRP piles. Figure 8 indicates that, they are 30ft. (9.14m) long with 14in. (35.6cm) diameter and reinforced with five No. 6 long steel bars and thirty-seven No.3 spiral steel ties in each pile for the FU-1. Auger-cast pile cap is reinforced with double No. 4 ties at 6 in. (152.4mm) o.c. in transverse direction at18 in. (457.2mm) height. The stirrups that are located at the center is 24 in. o.c. (609.6mm) and the exterior tie is 42 in. o.c. (1066.8mm) long as shown in Figure 4 with blue marking.

The C-shaped No. 5 steel bars that are located at 8 in. (203mm) back wall, splices the concrete deck bars and pile caps steel stirrups. The concrete deck is 3 in. (76.2mm) thickness and reinforced with No.3 at 8 in. (203mm) o.c. steel bar with hooked at each end. At the back wall, one hook No. 5 at 12in. (304.8mm) o.c. is placed at each stem as shown in Figure 4 with red marking. The Curb is reinforced with No.3 steel stirrups at 12 in. (304.8mm) o.c. in longitudinal direction. The steel stirrups tie the curb to the concrete deck. Two L-shape No. 4 steel hooks are placed at each face of double-tee.

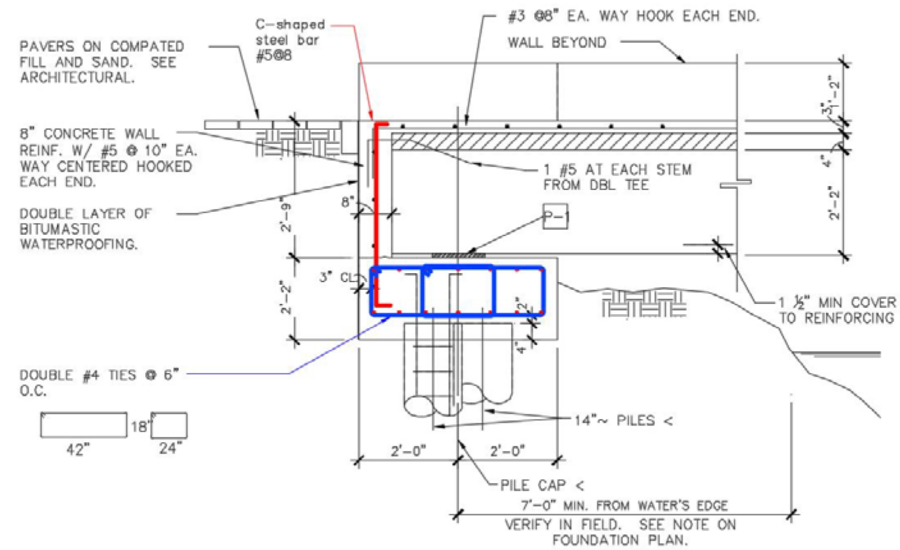

Figure 4: Longitudinal Section at FU-1 Decking

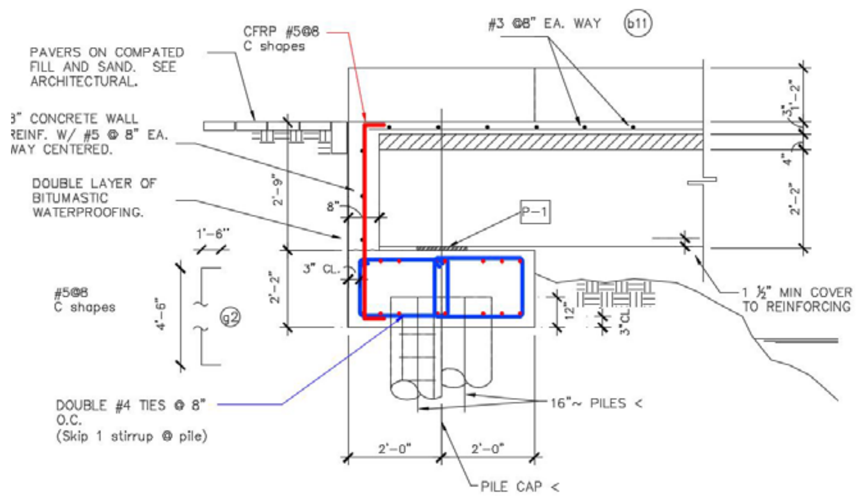

Figure 5: Longitudinal Section at FU-2 Decking

Chapter 5

FRP Reinforced Bridge (FU-2)

There are several publications about the bridge that are referenced in this paper. The following construction details are taken from an article published in Concrete International Magazine by American Concrete Institute (Antonio Nanni 2016). The "Innovation Bridge" construction was started in November 2015 and completed in May 2016. It is located in University of Miami campus and has a span of 70ft (21.3m). Figure 6 shows three-dimensional illustration of FU-2 structural components.

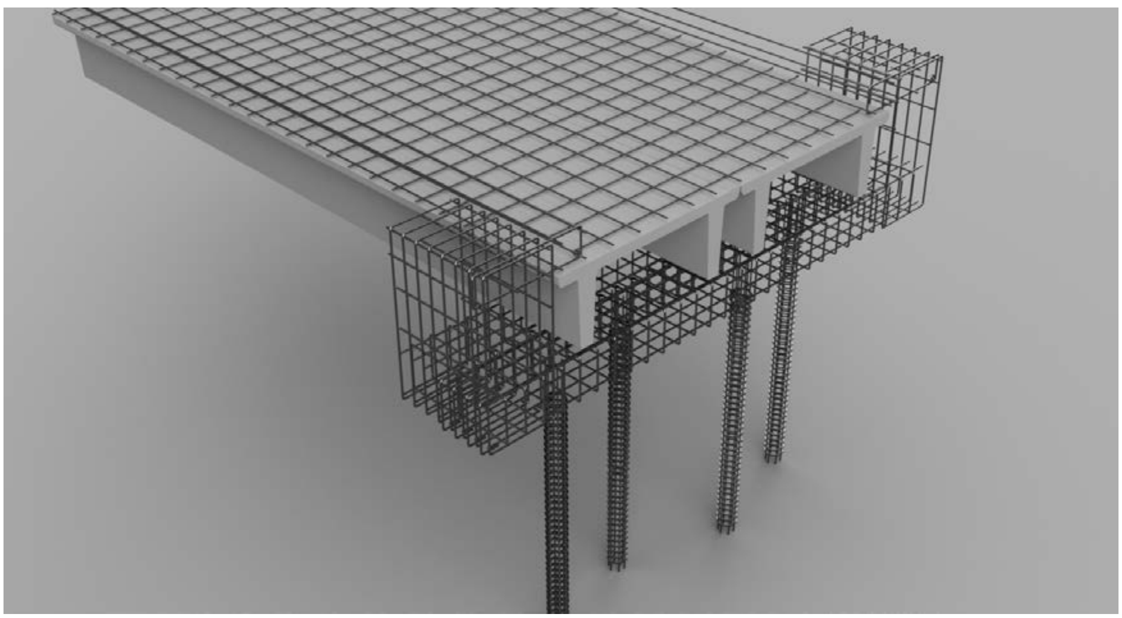

Figure 6: FU-2 Structural Rendering

Originally, the bridge design used traditional steel reinforced concrete. However, due to increasing interest in using alternative materials in the construction industry, engineers at the University of Miami Civil, Architectural and Environmental Department decided to use composite reinforcements instead of conventional steel reinforcement. The bridge includes precast pre-stressed girders, eight identical auger-cast piles, concrete cast-in-place pile caps, concrete curbs, concrete deck topping, side blocks and back walls. Stainless steel was used as a structural component for the double tee connections, due to necessity. After the decision was made to use composites as an alternative to steel reinforcement a new design was formulated by UM research team using the Fiber Reinforced Polymers. The three types of FRP used are GFRP, BFRP and CFRP.

Two precast double tees work as girders and four webs were pre-stressed with 0.6 in. (15mm) diameter seven-wire CFRP strands each web. Each strand was pre-tensioned to 42 kip (182 KN) and nine CFRP is placed in each stem. For the double tees, self-consolidation concrete was used. No.3 and No. 4 BFRP reinforcements at 6 in. (152mm) o.c. both way is placed over the stems and flanges.

A system for monitoring strain was installed as part of the research project. It consists of 16 vibrating wire gauges (VWGs) are embedded in the bridge deck to screen the strain reinforcement bars, concrete and pre-stressing tendons and to transmit length in the time of construction. Two encapsulated VWG are used on the BFRP bars that are located on top of stem and flanges in longitudinal direction and at the center of flanges in short direction.

The BFRP and GFRP reinforcement are used for side blocks, pile caps, back walls and deck topping. The cast-in-place concrete side blocks are 6ft (182cm) by 2.83ft (86cm) and reinforced with total of forty BFRP stirrups that are No. 5 at 8 in. (203mm) o.c. both ways in longitudinal direction as shown in Figure 3 with red marking. FU-2 uses closed BFRP stirrups contrary to FU-1 which is designed with C-shaped steel bars. Curbs are bound to side block with BFRP stirrup No. 4 at 8 in. (203mm) o.c. which is shown in Figure 3 with blue mark.

The cast-in-place pile caps consisted of No. 4 at 8 in. (203mm) o.c. BFRP double stirrups in transverse direction (Figure 5, blue marking). As shown in Figure 5, 19ft long No. 8 BFRP bars at 8 in (203mm) o.c. are placed at bottom and the top of pile caps. Moreover, the cast-in-place concrete back walls are reinforced with C-shape stirrups. They are twelve No.5 GFRP bars at 8 in. (203mm) o.c. in long direction as demonstrated in Figure 5 with red mark. No. 3 at 8 in. (203mm) o.c. BFRP bars are used for 3 in. cast-in-place concrete deck topping in both way and curbs were reinforced with continuous closed BFRP stirrup No.4 at 8 in. (203mm) o.c. in longitudinal direction (Figure 5).

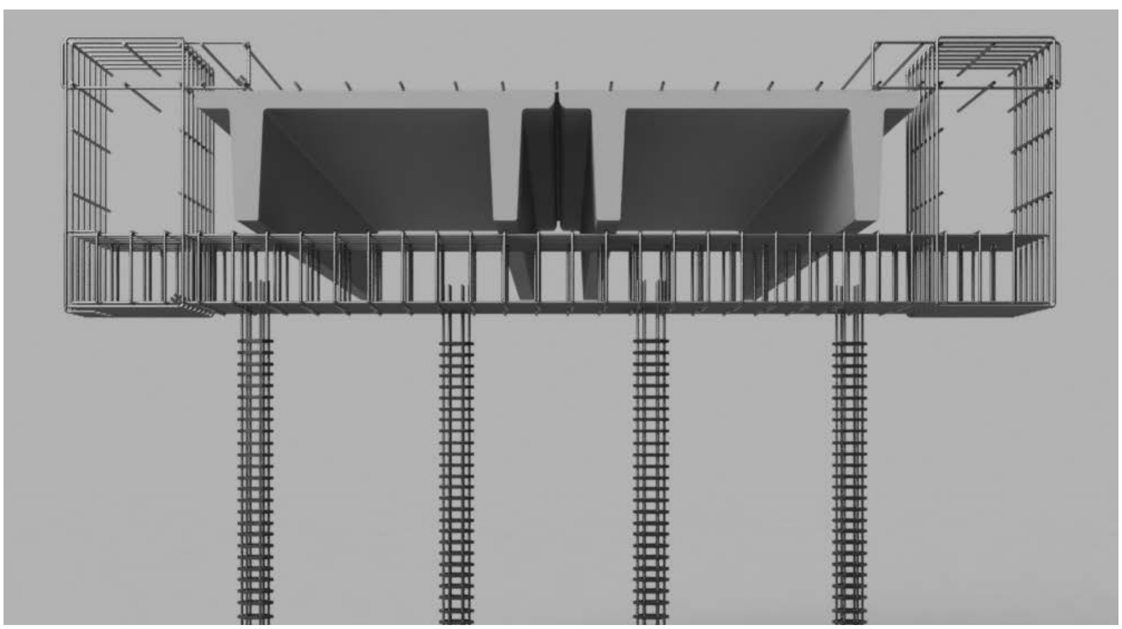

Figure 7: FU-2 Cross Section Rendering

The foundation consists of total of eight prefabricated auger-cast-piles which are 40ft (12.19m) long and 16 in. (406mm) diameter. Each end of the bridge has four of these piles installed. They are reinforced with No.3 at 6 in. (152.4mm) spiral BFRP. Compared to FU-1, 30 ft. auger cast piles FU-2 is designed with 40ft long six No.6 BFRP for each pile shown in Figure 8. Each cage was prefabricated and transported to the site.

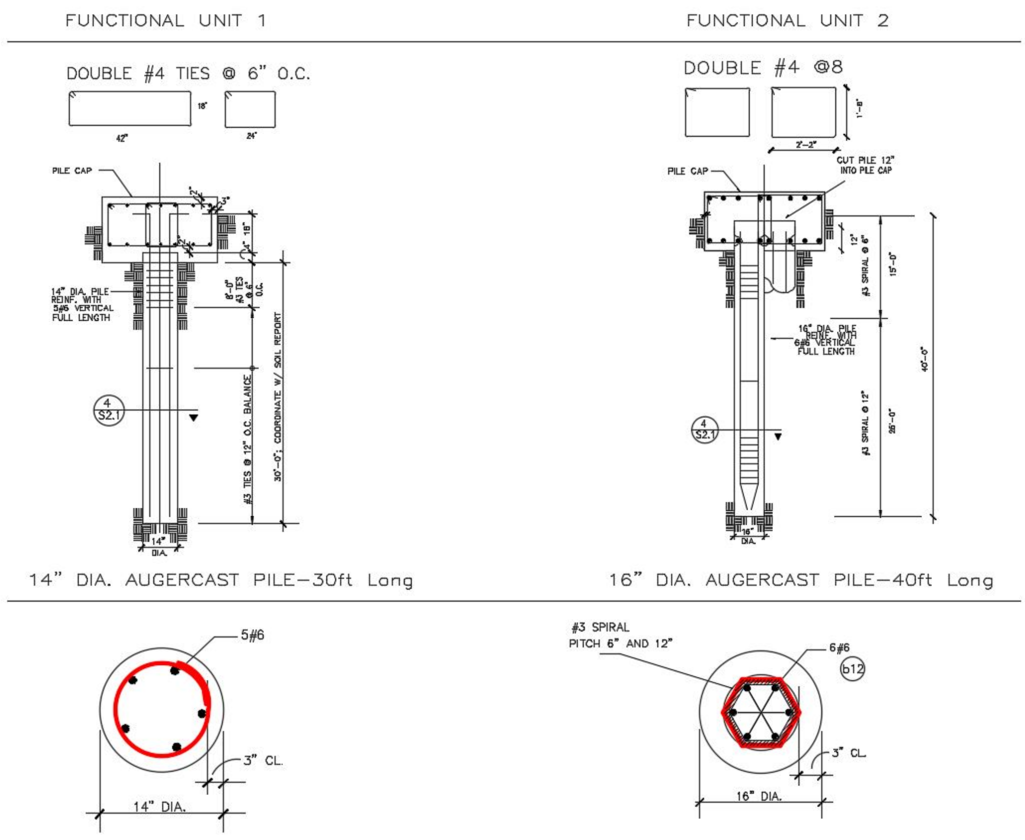

Figure 8: Auger Cast Pile Section of FU-1 on the right and FU-2 on the Right

Chapter 6

Life Cycle Phases

Life cycle phases provide a more depth in view of EI of each phase of a product's life. Each stage is formed by different activities depending on project itself. Stages consist of Materials Manufacturing, Construction, Use, Maintenance, and End of Life phases (Bayer et al., 2010). The complete LCA phases accounts for providing detailed information regarding EI of each FU's complete life cycle.

6.1 Materials Manufacturing Phase

The materials manufacturing phase is determined by accounting for the raw material acquisition and transporting raw materials to the manufacturing sites. Different LCA methodologies have four different process-based approaches of accounting for EI: Cradle-to-Grave, Cradle-to-Gate, Cradle-to-Cradle and Gate-to-Gate are these four process-based LCA methods.

Cradle-to-Grave is considered as full LCA process including material manufacturing phase "cradle" to the disposal of the product, which is "the grave". Cradle-to-Grave method serves to all the stages that has also potential impact during product's life such as extraction of raw materials, maintenance and disposal stages. Cradle-to-Gate is a partial LCA assessment gives information from extraction of material and manufacturing "cradle" to the "gate" which leaves the gate of the manufacture . Cradle-to-Cradle is a special approach to the product life cycle starting from manufacturing of the manufacture to the disposal stage. Although it seems similar to the cradle-to-grave method, it differs in terms of the way that considering disposal phase. The method relies on that disposal should be the stage that all product waste is recycled. Cradle-to-cradle term is developed by Michael Braungart and William McDonough and designed for taking the attention to the strategy which aims designing product that can be fully recycled at the end of its life and back to nature or used for new product rather than trying to use material with less EI. Gate-to-Gate is a method that is used to determine EI of specific material or stage within the entire life of the product. Gate-to-Gate approach can be linked to any phase of LCA based on research aspect.

LCI uses cradle-to-gate data collection as a system boundary and provides additional categories, which include the recycling properties of the material to improve accuracy. In this paper, cradle-to-grave method is used to assess overall cycle of the project and Cradle-to-Gate is used in LCI phase. In this study, there are several sources used to determine the Cradle-to-Gate EI.

The Inventory of Carbon and Energy (Hammond 2008) was used for determining EE and carbon emission of each material that is applied for the majority of the materials assessed in LCI. ICE was conducted with all the materials that were used in Functional Unit. For FU-2 materials, except FRP reinforcements, ICE was used to determine EI. The Eco Impact Calculator Tool (Association n.d.) which will be explained in detail under the EE section is used to calculate EE and carbon emission of FRP reinforcements. Following phases and calculations will be based on comparison of the two functional units.

FU-1 manufacturing phase includes, production and distribution of steel-rebar, cement, sand, aggregate, water, double tee steel plate flange. Due to the various range of strength of concrete component of the bridges, the average was taken 5000 psi (34.5 MPa) with ratio 1:1.6:2.

ICE includes detailed information for over two hundred material under thirty main categories. Each category is broken down into different mixture, ratio of property of that material. EE and carbon emission of the cement is determined based on the use of %25 fly ash (Table 1) . Double tee steel plate EE and carbon emission data is taken from steel plate primary section in LCI. The section selected for steel plate represents materials that can be recycled. Primary stands for predominantly virgin material.

To determine carbon emission and EE for steel reinforcement, “primary” category from steel-bar section from ICE is selected. In this study, two different alternatives will be considered by using virgin and recycled steel reinforcement. Since the study is based on comparing two different structural materials, if one of these materials is considered as virgin, the other material property has to account for virgin to be able to have accurate results. Hence, virgin FRP reinforcement is used beside virgin steel reinforcement. Following calculations are based on primary category (virgin steel-reinforcement) and virgin FRP reinforcement. On the other hand, one of the alternative scenarios that will be studied under the Alternative Scenarios section is calculated by using recycled steel reinforcement. However, due to lack of data on EI of recycled FRP reinforcements, it is hard to compare both material with their recycle properties.

Mass of steel reinforcements are calculated by determining linear mass density of each bar size. Table 1 compares total weight calculated based on mass density for each number of steel reinforced used for FU-1 and total weight calculated based on average 490 lbs. per sq. ft.

	lb/ft	Total Weight (lbs)	Total Weight (lbs=490 lb/ft3)	Total Volume
#3	0.376	2416.592	2406.051	4.910
#4	0.668	2066.150	2106.669	4.299
#5	1.043	1350.385	1363.979	2.784
#6	1.502	5285.057	5258.667	10.732

Table 1: Linear Mass Density Comparison for Steel-Reinforcement (1 lbs. = 0.454 kg)

For assessing EI of double tee flange connection, steel plate sub-category in ICE steel database is used and 490lb./ft.3 is estimated to calculate total impact.

Total mass of concrete is 80.63 tons and steel-reinforcement weight is 6.42 tons as it is shown in Table 2.

Functional Unit 1 (Steel-reinforced Bridge)						
Description	Material	Units	Weight (lbs.)/unit	Total Volume (ft3)	Total Weight (lbs.)	Mass (Kg)
All concrete mix	*- Cement (25% fly ash)*	19.83% of concrete wt. lb./cu.ft.	139.7	356.63	49820.65	22598.25
5000 psi	*- Sand*	31.39% of concrete wt. lb./cu.ft.	139.7	564.52	78863.86	35772.02
	- Aggregates	40.83% of concrete wt. lb./cu.ft.	139.7	734.29	102580.80	46529.83
	- Water	7.95% of concrete wt. lb./cu.ft.	139.7	142.97	19973.48	9059.81
Steel	#3	lb./ft.	0.376	4.91	2416.59	1096.15
Steel	#4	lb./ft.	0.668	4.30	2066.15	937.19
Steel	#5	lb./ft.	1.043	2.78	1350.38	612.52
Steel	#6	lb./ft.	1.502	3.91	5285.06	2397.26
Steel	#8	lb./ft.	2.67	35.42	1725.63	782.73
Double Tee Flange Connection	Stainless Steel	lb/ft3	490	0.19	90.78	41.18

	Total Weight (kg)	Total Weight (Tons)
Concrete	73142.78	80.63

Table 2: Unit weights, Total Volume and Total Mass for FU-1 (1 lbs. = 0.454 kg)

Two Functional Units are designed with same amount of stainless steel that is embedded into curbs for lightning devices. Therefore, it is omitted for the following calculations because both bridge designs used same amount of stainless steel.

Functional Unit 2 (Fiber Reinforced Polymer Bridge)						
Description	**Material**	**Units**	**Weight (lbs.)/Unit**	**Total Volume**	**Total Weight (lbs.)**	**Mass (Kg)**
All concrete mix	*- Cement (normal wt.)*	19.83% of concrete wt. lb./cu.ft.	139.7	393.50	54971.38	24934.58
5000 psi	*- Sand*	31.39% of concrete wt. lb./cu.ft.	139.7	622.89	87017.23	39470.32
	- Aggregates	40.83% of concrete wt. lb./cu.ft.	139.7	810.21	113186.15	51340.33
	- Water	7.95% of concrete wt. lb./cu.ft.	139.7	157.76	22038.45	9996.46
BFRP	#3	lb./ft.	0.132	1.839	560.50	254.24
BFRP	#4	lb./ft.	0.220	3.474	881.39	399.79
BFRP	#5	lb./ft.	0.465	2.880	622.89	282.54
BFRP	#6	lb./ft.	0.494	5.857	948.72	430.33
BFRP	#8	lb./ft.	0.881	33.227	534.18	242.30
GFRP	#5	lb./ft.	0.287	0.645	86.1	39.05
CFRP	#5	lb./ft.	0.249	4.34	556.60	252.47
Double Tee Flange Connection	Stainless Steel	lb/ft3	490	0.19	90.78	41.18

	Total Weight (kg)	Total Weight (Tons)
Concrete	84924.56	93.61
Double Tee	40817.13	44.99
FRP	1900.72	2.10

Table 3: Unit weights, Total Volume and Total Mass for FU-2 (1 lbs. = 0.454 kg)

FU-2 material and manufacturing phase includes same concrete properties, 5000 psi and the same concrete mixing ratio as FU-1. Table 3 categorizes FRP bars and their weight per ft., which is lighter than steel reinforcement. Table 3 indicates that the total mass of concrete is 93.61 tons and FRP reinforcement is 2.10 tons.

6.2 Construction Phase

The construction phase accounts for activities such as transportation of the materials to the construction site, construction equipment, and power tools that are used and consume energy during the construction process. For both bridge designs, the concrete double tee is fabricated in manufacturing factory and transported to the site. CFRP is embedded into concrete double tee at the manufactures site. Steel reinforcement is considered as they are also placed to double tee which is manufactured at the same manufacture company then transported to the site. Number and transportation of workers involved in both bridge project is considered same and omitted from the study.

The material transportation accounts for a significant part of the energy consumption in the overall LCA of the project. EPA's Motor Vehicle Emission Simulator (U.S. EPA MOVES (2010b) 2010) is used to calculate EI that occurs during the transportation of the materials. County Scale database ONROAD model is selected.

FU-1 and FU-2 both transport cement and aggregate from the Pennsuco Plant in Medley, FL. For FU-1, sand is taken from Clermont and brought to the Pennsuco Plant for the concrete mixture. After the concrete mix is prepared at the Pennsuco Plant, it is transported to the double tee manufacturer in Medley, FL. After the double tees reinforced is prepared at Medley, they are sent to the University of Miami construction site.

Steel plant is selected as closest location. Double tee flange connections are brought to the site from 10.3 miles (16.58km) away, from Miami, FL. Ready-mix concrete is transported to the site from South Miami ready-mixed concrete plant which is located 3 miles away from the University of Miami construction site.

Table 4 shows detailed tabulation of transportation path of all construction materials. Jacksonville steel plant is selected as steel reinforcement supplier. There are number of steel plants in United States and Jacksonville plant is the closest plant to the construction site.

	Materials	Location	Distance (km)
Functional Unit 1	Rebar	Jacksonville, FL (Gerdau Plant)	634.08
	Cement to Plant	Medley,FL (Pennsuco Plant)	22.53
	Sand to Plant (Concrete)	Center Sand,Clermont	413.60
	Sand to Plant (Double Tee)	Center Sand,Clermont	397.51
	Aggregates to Plant	Medley,FL (Pennsuco Plant)	22.53
	Fly Ash to Plant (Concrete)	Jacksonville	579.36
	Fly Ash to (Double Tee)	Jacksonville	566.49
	Ready-mixed to UM	South Miami Titan Ready-Mix	4.83
	Concrete Mix to Coreslab	Medley,FL (Pennsuco Plant)	1.13
	Double Tee Precast	Medley,FL (Coreslab Structures)	28.32
	Double Tee Flange	Miami,FL	16.58
Functional Unit 2	BFRP	Pompano Beach	96.24
	CFRP	Tokyo-Miami	23661.63
	GFRP	Seward, NE	2859.80
	Cement to Plant	Medley,FL (Pennsuco Plant)	22.53
	Sand to Plant (Concrete)	Center Sand,Clermont	413.60
	Sand to Plant (Double Tee)	Center Sand,Clermont	397.51
	Aggregates to Plant	Medley,FL (Pennsuco Plant)	22.53
	Fly Ash to Plant (Concrete)	Jacksonville	579.36
	Fly Ash to (Double Tee)	Jacksonville	566.49
	Ready-mixed to UM	South Miami Titan Ready-Mix	4.83
	Concrete Mix to Coreslab	Medley,FL (Pennsuco Plant)	1.13
	Double Tee Precast	Medley,FL (Coreslab Structures)	28.32
	Double Tee Flange	Miami,FL	16.58

Table 4: Material Transportation Data, (1 km = 0.621 miles)

FU-2 used transportation methods and manufacturers for cement, aggregate, sand and ready-mix concrete same as FU-1. However, the mass of concrete is 10.38 tons more than FU-1. FU-2 contains FRP reinforcement and the transportation of each FRP reinforcement type is shown in Table 3. BFRP is fabricated in Pompano Beach and GFRP in Nebraska and then transported to the site. It is brought to the site using different means of transportation. CFRP is manufactured in Tokyo and transported to Tokyo Port located 3 miles away with short-haul truck. From the Tokyo Port, it is shipped to Shanghai Port first and then from Shanghai to Miami by ocean shipping using diesel fuel. Distances used for FRP reinforcement transportation are based on actual distances between manufacturer and construction site while the steel reinforcement manufacturer is selected as closest plant.

		Vehicle	Total Weight(kg)	Number of Trucks	Total Distance (km)
Material Transportation	Functional Unit 1 (Steel-reinforced Bridge)	Dump Truck (Rebar)	4796.65	0.3021	383.16
		Concrete Truck (Ready Mix from South Miami Plant to UM)	73142.78	4.6072	44.49
		Semi-Trailer (Double Tee)	40817.13	2.5710	145.65
		Pickup Truck(Double Tee Flange)	41.18	0.0026	0.09
		Concrete Truck for Cement (Pennsuco to South Miami Plant)	14504.21	0.9136	41.17
		Concrete Truck for Sand (Center Sand to South Miami Plant)	22959.52	1.4462	1196.30
		Concrete Truck for Aggregate (Pennsuco to South Miami Plant)	29864.20	1.8811	84.77
		Concrete Truck for Sand (Center Sand to Pennsuco Plant)	12812.50	0.8070	641.62
		Concrete Truck (Pennsuco Ready Mix to Coreslab)	40817.13	2.5710	5.79
	Functional Unit 2 (Fiber Reinforced Polymer Bridge)	Medium Duty Truck (BFRP)	1348.73	0.0850	16.35
		Pickup Truck (CFRP)	252.47	0.0159	0.50
		Pickup Truck (GFRP)	39.05	0.0025	14.07
		Concrete Truck (Ready Mix from South Miami Plant to UM)	84924.56	5.3493	51.65
		Semi-Trailer (Double Tee)	40817.13	2.5710	145.65
		Pickup Truck(Double Tee Flange)	41.18	0.0026	0.09
		Concrete Truck for Cement (Pennsuco to South Miami Plant)	16840.54	1.0608	47.80
		Concrete Truck for Sand (Center Sand to South Miami Plant)	26657.82	1.6792	1389.00
		Concrete Truck for Aggregate (Pennsuco to South Miami Plant)	34674.70	2.1841	98.42
		Concrete Truck for Sand (Center Sand to Pennsuco Plant)	12812.50	0.8070	641.62
		Concrete Truck (Pennsuco Ready Mix to Coreslab)	40817.13	2.5710	5.79
		Vehicle	**Total Weight(kg)**	**Number of Trucks**	**Total Distance (km)**
		Maritime	252.47	1.0000	47272.91

Table 5: Means of Transportation and Vehicle Capacity (2016), (1 km = 0.621 miles, 1 lbs = 0.454 kg, Truck Trips = 1 Truck one way based on weight)

Table 5 indicates the vehicles that are used for transportation of the materials and total distances from manufacturer to the site. Number of trucks is calculated from mass of the material and divided by capacity of trucks used, which is 15875.73 kg.

Site equipment is temporarily used during construction depending on material application. The type of equipment used, vehicles and their total operation hours are provided by the site engineer, Guillermo Claure.

	Equipment	Horsepower (hp)	Fuel Type	Hours
Site Vehicles	75-t crane (Concrete Bucket)	238	Gas	32
	40-t crane (Double tee)	242	Gas	6
	5.4-t crane (FRP)	57.4	Gas	16
	Backhoe	94	Gas	16
	Drill Rig	443	Diesel	16
	Concrete Vibrator	2	Gas	32

Table 6: Equipment Schedule

Hour based emission factors for site equipment and vehicle is taken from the LCA study, which used USEPA NONROAD (USEPA 2010) report and it is shown in Table 6 with horsepower. Power tools electricity is generated from University of Miami. Drill rig is applied for auger-cast piles construction. Both bridge design is considered to use same kind of site equipment and vehicles except FRP transportation.

6.3 Use and Maintenance Phase

This phase includes system the operation, the energy consumption during given life span and the repair or replacement of the structure. Transportation of materials or vehicle used during maintenance is also considered in this stage.

Bridges are constructed with their predicted service life. However, each material in bridge construction has its own properties and contributes different maintenance, life span, strength and durability. There are number of projects that investigated the life span of bridges

Using concrete-specific service-life models it is possible to provide information about service life of steel reinforced concrete bridge. Steel reinforced concrete exposed to chlorine environment causes decreased life span. Expected service life for steel reinforced concrete bridge is 75 years without considering the cracking that occurs on concrete over time. Service-life prediction models in this study do not consider presence of steel reinforcement. Thus, with the consideration of reinforcement predicted life span might be accounted for 55 years. (Dale P. Bentz 2014).

FRP composites have noncorrosive properties and one of the reason that they have been applied in the construction field is because of their longer life span expectations. However, lack of long term studies currently prevents estimating service life of FRP reinforced bridge. One of the studies states that its service life can change between 30-100 years depending on environmental conditions (Karbhari 2007).

Another study working on highway bridges shows that average service life of typical bridges is 43 year in U.S. Figure 9 shows distribution of U.S. bridges by age (Crevello 2015).

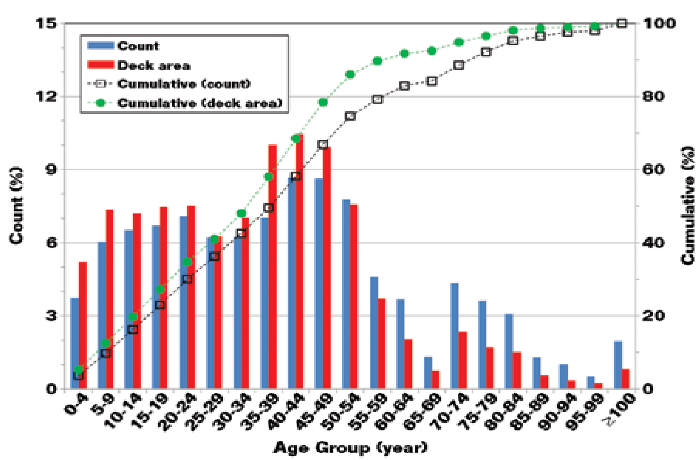

Figure 9: Age Distribution of U.S. Bridges

Most bridges initially are designed for 50-year service life but under different environmental conditions, service life might differ. Service-Life Prediction State-of-the-Art Report states that Eurocode leads 50-years life span, however this indicator does not include all environmental parameters. Thus, the predicted life span might decrease due to environmental conditions (Clifton 2000).

The life span of FRP bridge changes depend on type of FRP as structural component. Predicted service life for the bridges designed by FRP deck is 100 years (FRP bridge decking – 14 years and counting- Scott Reeve). Another study conducted a comparative research on bridge structure using three different reinforcement which is CFRP bar, epoxy-coated steel reinforcement and black (i.e. without epoxy-coating) steel reinforcement with cathodic protection. Figure 10 indicates required maintenance during the bridge service life using CFRP and steel reinforcement. The bridge with CFRP reinforcement requires deck replacement after 80 years while the steel reinforced bridge needs replacement after 40 years (Eamon 2012).

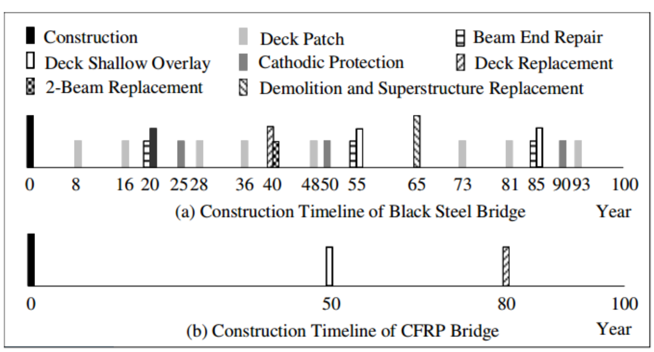

Figure 10: Activity Timeline-Mean Times (inspections not shown (Eamon 2012))

Use and maintenance phase is directly related to life span of the structure and the maintenance data carried out by Eamon C. D. is used to make assumptions for the maintenance phase. The service life information is used in the end-of-life calculations. The major EI is contributed by deck replacement through the construction time line. Thus, other maintenance needed for both FUs is omitted.

It is assumed that FU-1 will require deck replacement after 40 years while FU-2 will require after 80 years. FU-1 service life is considered 65 years and it is 100 year for FU-2.

There are different deck removal methods and sawing is commonly used bridge deck removal method. The concrete deck is cut by diamond saw into pieces and they are removed by crane (Brent Phares 2014). Table 7 indicates equipment used during removal and replacement of the deck, hours operated and EI.

	Equipment	Horsepower (hp)	Hours	Fuel (Gal/hr)	CO2(kg/hr)	Fuel (GJ/gal)	EE (GJ)	CO2 (kg)
Site Vehicles	75-t crane (Concrete Bucket)	242	5.5	16.21	140.97	0.155	13.82	775.31
	40-t crane (Double tee)	238	6	15.95	138.64	0.155	14.83	831.81
	5.4-t crane (Reinforcement)	57.4	16	3.85	33.44	0.155	9.54	534.97
	Diamond Blade Saw (Removal)	59	4	3.95	34.37	0.155	2.45	137.47
	75-t crane (Removal)	238	4	15.95	138.64	0.155	9.89	554.54

Table 7: Site Equipment for Maintenance

Carbon emission and EE of new deck is calculated based on material, transportation and equipment impacts. Weight of concrete and reinforcement used for decking is determined. Table 8 shows tabulation of materials used for deck replacement.

Material	Total Weight (kg)	EE (MJ/kg)	Total EE (MJ)	CO2/kg	Total CO2 (kg)
Steel for Deck	1856.08	36.4	67561.35	2.68	4974.30

	Material	Units	Total Weight (Kg)	EE (MJ/kg)	CO2/kg	Total EE (MJ)	Total CO2 (kg)
Double Tee	*- Cement (20% fly ash)*	19.83% of concrete wt. lb./cu.ft.	8094.04	3.52	0.62	28491.01	5018.30
	- Sand	31.39% of concrete wt. lb./cu.ft.	12812.50	0.1	0.005	1281.25	64.06
	- Aggregates	40.83% of concrete wt. lb./cu.ft.	16665.64	0.1	0.005	1666.56	83.33
	- Water	7.95% of concrete wt. lb./cu.ft.	3244.96	0.2	0	648.99	0.00
Concrete (for decking)	*- Cement (20% fly ash)*	19.83% of concrete wt. lb./cu.ft.	2514.94	3.52	0.62	8852.57	1559.26
	- Sand	31.39% of concrete wt. lb./cu.ft.	3981.03	0.1	0.005	398.10	19.91
	- Aggregates	40.83% of concrete wt. lb./cu.ft.	5178.26	0.1	0.005	517.83	25.89
	- Water	7.95% of concrete wt. lb./cu.ft.	1008.26	0.2	0	201.65	0.00

Table 8: Materials used for Maintenance for FU-1

Due to removal and placing new deck for FU-1, additional EI must be added to the use and maintenance phase. During 65 years of FU-1 service life, FU-1 deck needs to be replaced. However, FU-2 deck will be functioning in this period. After 80 year of service life of FU-2, there will be a deck replacement for FU-2.

6.4 End-of-Life Phase

The phase refers to energy consumed during the demolition of the project, material transportation needed and material reuse or recycling at the time of deconstruction.

There are two main method to recycle FRP composites, mechanical and thermal method. Beside mechanical method, thermal method provides a technique to separate polymer matrix and fiber reinforcement from each other and allow reusing (Correia 2011).

For last decades, FRP composites have been extensively used and its waste management becomes an important issue. One of waste management method is to cut FRP rebar waste and use as coarse aggregate in concrete production. The study determines mechanical properties of the concrete using FRP rebar waste as aggregate. They incorporate the same GFRP reinforcement used in FU-2 as a waste. The ingredient information which are vinyl ester resin and ECR glass fibers are provided by manufacturer. The study shows that using FRP rebar waste in concrete production is a potential method (Ardavan Yazdanbakhsh 2016).

Beside the studies are conducted on the use of FRP waste, there is a lack of research on possibilities of producing FRP with recycled content. Thus, in this paper, FRP reinforcements are considered as virgin material and EI of recycling phase is omitted due to lack of information. Recycled steel is also not used in the base comparison so the materials are compared on an equal basis. Their disposal is determined to be sent to the landfill same as steel-reinforcement.

RS Means 2016 is used to determine equipment used for demolition of the structure and horsepower, EE and CO2 emission data is taken from the study which used “Exhaust Emission Factors for Nonroad Engine Modeling—Spark Ignition” (Matthew Trussoni 2014)

	Equipment	Horsepower (hp)	Fuel Type	Hours	Fuel (Gal/hr)	CO2(kg/hr)	Fuel (GJ/gal)	EE (GJ)	CO2 (kg)
Demolition	20 Ton Crane	150	Gas	13	10.05	87.375	0.155	20.25	1135.875
	Skid Loader	100	Gas	15	6.70	58.25	0.155	15.58	873.75
	Dump Truck	400	Gas	6	26.80	233	0.155	24.92	1398

Table 9: End-of-Life Equipment Detail

The MOVES software data input is used to evaluate EI of vehicles for the year 2081 and the year 2116. The distance for round trip to move the materials to the landfill is selected as closest landfill for construction waste and it is assumed 34.92 km (21.7 miles). Table 10 gives data calculated by using MOVES software. Single Unit Short-haul trucks are used to transport waste from the site.

		CO2 (kg/km)	EE (MJ/km)
2081	Single Unit Short-haul Truck	0.58	7.99
	Combination Short-haul Truck	1.03	14.14
	Combination Long-haul Truck	1.15	15.74

		CO2 (kg/km)	EE (MJ/km)
2116	Single Unit Short-haul Truck	0.54	7.48
	Combination Short-haul Truck	0.99	13.62
	Combination Long-haul Truck	1.11	15.25

Table 10: EI of Vehicles Used During Demolition

Chapter 7

Results and Interpretation

LCI is a part of LCA for quantifying inputs and outputs of the product cycle. The last phase of a LCA is the LCIA, where data is interpreted based on the LCI and associated life cycle phases which contributes throughout product's entire life cycle. The LCI includes the data calculated from each phase which is material and manufacturing, construction, use and maintenance, and end-of-life. The LCIA classifies these indicators in respect of LCI.

Figure 11 shows framework of LCIA and is combined with LCA phases (ISO 14042:2000)

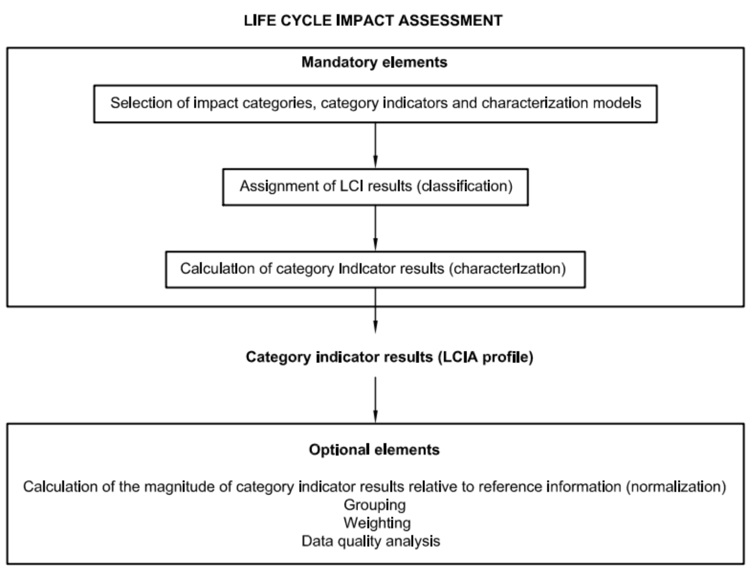

Figure 11: LCIA Principle

7.1 LCIA Phases

In this paper, potential EI are categorized under mass of material, EE and carbon emission. All LCIA phases are indicated based on comparison of steel reinforced bridge (FU-1) and FRP bridge (FU-2). Three different case will be considered. Base case used 80 year equal predicted service life for FU-1 and FU-2 (Figure 12) and following calculations are conducted with base case. Scenario-1 was calculated considering the usage of recycled steel reinforcement instead of virgin material. Scenario-2 is based on 65 year life span with the deck replacement requirement after 40 year for FU-1 and 100 life span with deck replacement in 80th year of service life for FU-2. Last scenario, alternative scenario-3 was calculated using 43 year service life for FU-1 and 75 year for FU-2. In this case, it is assumed that no deck replacement is needed for both FUs. The focus to calculate these scenarios is to be able to compare different parameters. While base case uses same life span, scenario-2 includes calculations for maintenance phase of both FUs and the scenario-3 discusses the EI when no maintenance is needed for both FUs.

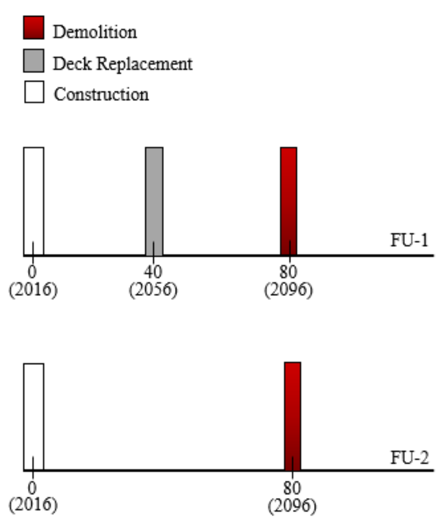

Figure 12: Base Case Timeline for Both FUs

7.1.1 LCIA: Mass of Materials

Two functional units are compared referring to their mass properties. Each functional unit consist of three structural materials which is concrete, reinforcement and stainless steel plate. Due to same weight of steel plate in used for two functional units, it is omitted for this phase. Despite their similar design principles of two bridges, they include different volumes of concrete due to different size of auger-pile used.

Concrete mass of FU-1 is 125.62 tons and includes concrete used for side walls, piles, pile caps, concrete curbs, deck topping, side blocks and back walls and double tee. FU-2 is formed by 138.61 tons of concrete which is 10.34% more than FU-1 (Figure 12).

The significant difference in the mass of material comes from reinforcement and these two system differ from each other with reinforcement selection applied in project. FU-1 has steel reinforcement and FU-2 uses FRP bars. The mass of reinforcement designates 4.86% of entire mass of bridge for FU-1 and 1.49% of FU-2.

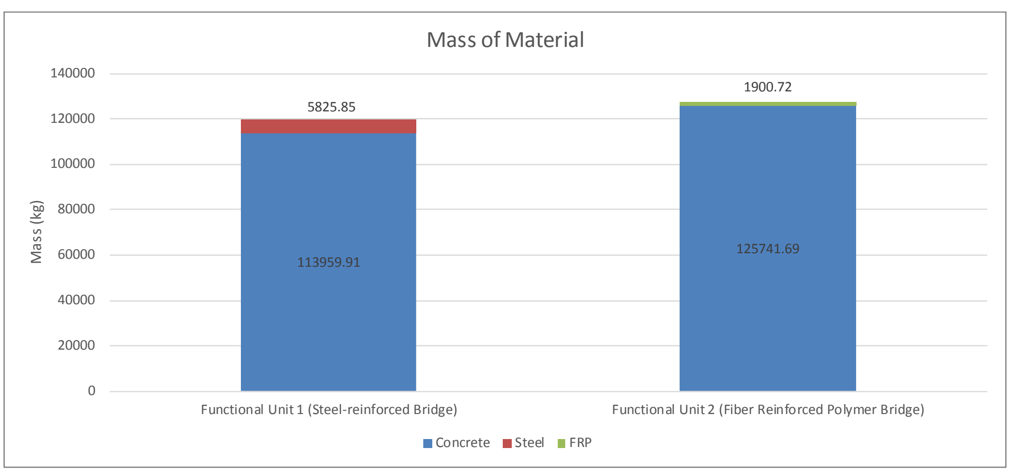

Figure 13: Mass of Concrete and Mass of Reinforcement Comparison (1 lbs. = 0.454 kg)

Figure 13 shows overall mass of reinforcement calculation for both structures. Mass of steel reinforcement is 6.42 tons and 2.1 tons of FRP mass. As it is stated, one of the advantages of FRP rebar is its light weight compared to steel rebar. Mass of FRP is 32.63% is less than steel-reinforcement.

7.1.2. Embodied Energy (EE)

EE is consumed each phase of LCA process. EE is presented in mega joules (MJ) and calculate separately for both Functional Units and for each phase. However, it is shown separately for material and manufacturing phase and combined for the construction and maintenance phase. Due to the difference between mass of concrete within two bridge design EE results varies.

Figure 14 indicates EE, which contributes energy consumed by manufacturing of concrete, steel and FRP reinforcement. EE data for concrete is considered separately for each individual material as it is done for mass of material section. The concrete is composed of cement with 20% fly ash, sand, aggregate and water. EE data for ingredients is taken from ICE per kg.

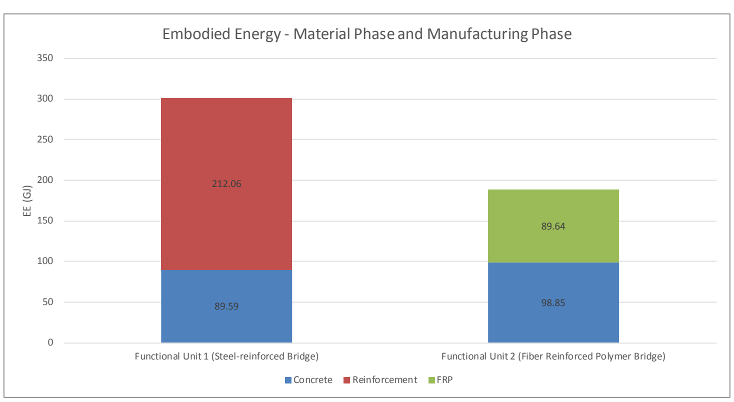

Figure 14: Total amount of EE for Materials Manufacturing Phase (1 lbs. = 0.454 kg)

Table 11 shows how the materials are tabulated regarding to EE and carbon emission. As it is demonstrated, virgin steel reinforcement has highest EE per kg.

Material	Total Weight (kg)	Embodied Energy (MJ/kg)	Total Emb. Energy (MJ)
- Cement (20% fly ash)	22598.25	3.52	79545.84
- Sand	35772.02	0.1	3577.20
- Aggregates	46529.83	0.1	4652.98
- Water	9059.81	0.2	1811.96
Steel	5825.85	36.4	212061.02

	Total EE (MJ)
Concrete	79545.84
Steel	212061.02

Table 11: FU-1 Embodied Energy Distribution

Reinforcement EE is indicated as steel reinforcement for FU-1. FU-2 reinforcement is formed by three different FRP rebar which are BFRP, GFRP and CFRP. EE for FRP is calculated by using Eco Impact Calculator Tool, which is launched by European Composites Industry Association (http://ecocalculator.eucia.eu/). The tool uses LCA method to contribute EI of composites from cradle-to-gate. Manufacturers and converters in Europe provide inventory data used in the software. Tool provides four predefined conversion process that indicates he method used for production of selected composite. These conversion processes are pultrusion, resin infusion (RI), resin transfer molding (RTM) and SMC/BMC molding. However, it also allows user to apply their own process. In this paper, RI conversion process is used to calculate EI. After conversion process is defined, second step is to add materials, quantify the mass and create material recipe. Glass Fiber Assembled Roving is selected as material under the category of Fiber Reinforcement and it is calculated as virgin material as it is used for base case.

Calculated cumulative energy demand for created recipe is used for EE calculations of BFRP and CFRP. 47.16 MJ/kg is the unified energy demand for FRP rebar used in FU-2 as it is shown in Table 12.

Material	Total Weight (kg)	Embodied Energy (MJ/kg)	Total Emb. Energy (MJ)
- Cement (25% fly ash)	24934.58	3.52	87769.71
- Sand	39470.32	0.1	3947.03
- Aggregates	51340.33	0.1	5134.03
- Water	9996.46	0.2	1999.29
BFRP	1609.20	47.16	75889.67
GFRP	39.05	47.16	1841.80
CFRP	252.47	47.16	11906.49
	Total EE (MJ)		
Concrete	87769.71		
FRP	89637.96		

Table 12: FU-2 Embodied Energy Distribution

Figure 15 demonstrates the comparison between FU-1 and FU-2 in terms of EE of Construction Phase.

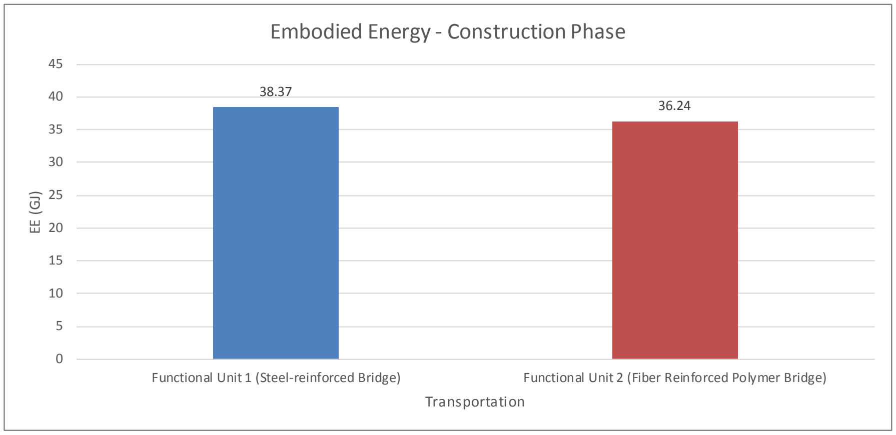

Figure 15: Embodied Energy of Construction Phase

Use and maintenance phase was conservative due to unknown parameters regarding the types of maintenance applications. Only deck replacement is considered throughout this phase. FU-1 deck will be replaced after 40 years and FU-2 will not require any deck replacement.

Figure 16 shows the total amount of EE will be produced. During FU-1 service life, FU-2 will function without requiring any deck replacement, thus, it is considered as zero. As a result, FU-1 deck maintenance leads 212.68 GJ EE.

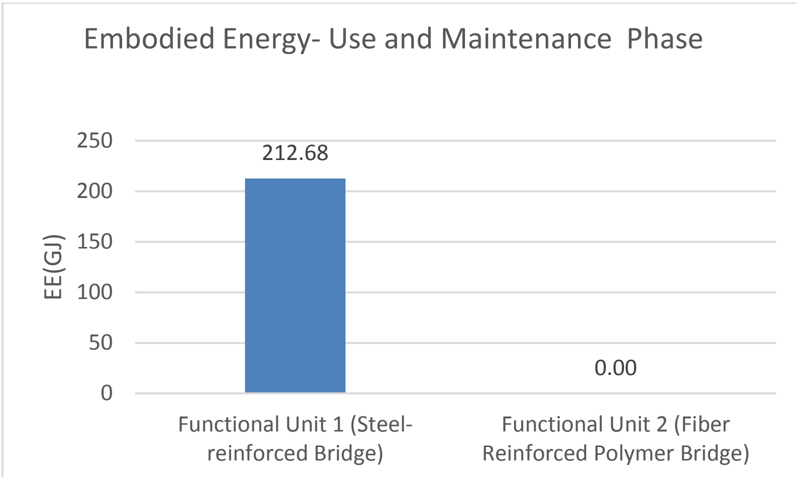

Figure 16: Embodied Energy – Use and Maintenance Phase (Base Case)

Figure 17 illustrates end-of-life EE distribution for both FUs. Due to the higher mass of concrete used for FU-2 construction, end-of-life phase transportation emission data is 0.32 GJ higher. Unit EE for trucks that are used during demolition in year 2096 is calculated by using the data base taken from MOVES software. Single Unit Short-Haul Truck data is applied for all the trucks. EE is 0.0078GJ/km.

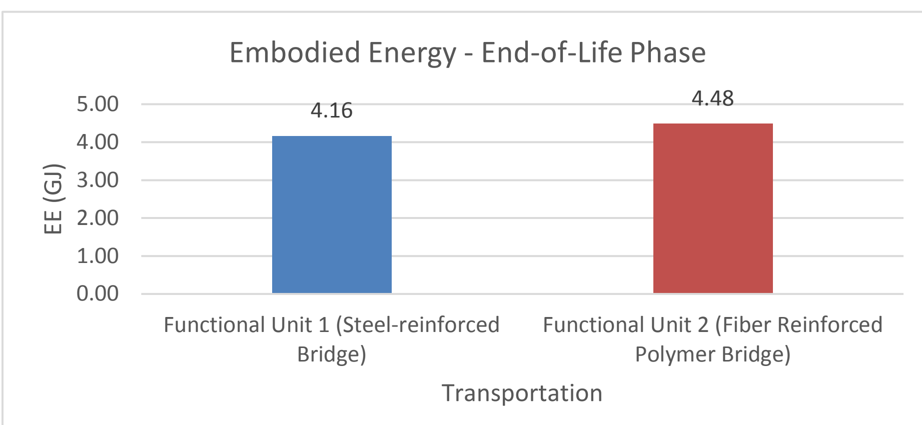

Figure 17: Embodied Energy – End-of Life Phase

Figure 18 demonstrate overall EE for base case calculation is based on initial case which FU-1 and FU-2 serve for 80 year and FU-1 requires deck replacement after 40 year. Total EE of FU-1 for base case includes Material, construction, use and maintenance, end of life. EI of demolition is the same for both FU-1, thus it is omitted for this case.

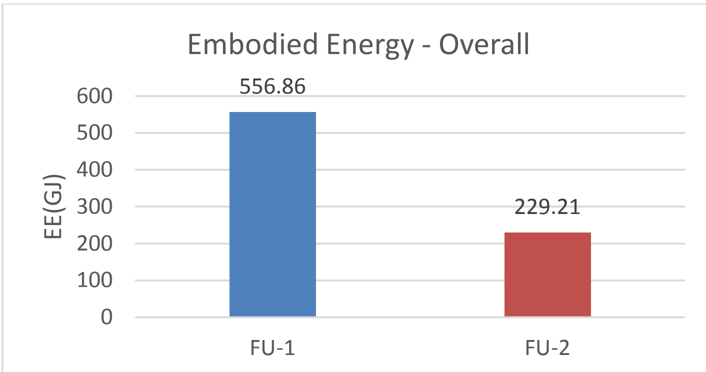

Figure 18: Overall Embodied Energy (Base Case)

7.1.3 Carbon Emission

Every phase that introduces EE results will also have carbon emission calculations. Material and manufacturing phase will compare FU-1 and FU-2 for concrete and reinforcement separately. Carbon emission data is taken from ICE for each material per kg as it is shown in Table 13 for FU-1.

Material	Total Weight (kg)	CO2/kg	Total CO2 (kg)
- Cement (20% fly ash)	22598.25	0.62	14010.92
- Sand	35772.02	0.005	178.86
- Aggregates	46529.83	0.005	232.65
- Water	9059.81	0	0
Steel	5825.85	2.68	15613.28

	Total CO2 (kg)
Concrete	14422.42
Steel	15613.28

Table 13: FU-1 Material Carbon Emission

Water carbon emission is omitted. Stainless steel plate and steel reinforcement has higher carbon emission due to carbon dioxide released during their manufacturing process for FU-1. Table 14 demonstrates FU-2 carbon emission distribution.

Material	Total Weight (kg)	CO2/kg	Total CO2 (kg)
- Cement (25% fly ash)	24934.58	0.62	15459.44
- Sand	39470.32	0.005	197.35
- Aggregates	51340.33	0.005	256.70
- Water	9996.46	0	0
BFRP	1609.20	3.33	5358.62
GFRP	39.05	3.33	130.05
CFRP	252.47	3.33	840.73
	Total CO2 (kg)		
Concrete	15913.49		
FRP	6329.40		

Table 14: FU-2 Material Carbon Emission

Carbon emission, which is proportional to mass of material, is higher compared to FU-1, because more concrete used in FU-2. Concrete carbon emission is increased by 1471.90 kgCO2 in FU-2 because the design changed and it brings about changes in mass of concrete, as it is shown in Figure 12.Carbon emission of reinforcement applied in FU-2, which are BFRP, CFRP and GFRP is 3.33 CO2 per kg.

Steel reinforcement used in FU-1 produces 7392.98 kgCO2 more than FU-2.

Although FRP reinforcement has higher EI than steel reinforcement per unit, it is lighter than steel and the total mass is reduced by using FRP reinforcement. Total reinforcement carbon emission is decreased by 42.49% by using FRP reinforcement, as it is demonstrated in Figure 19.

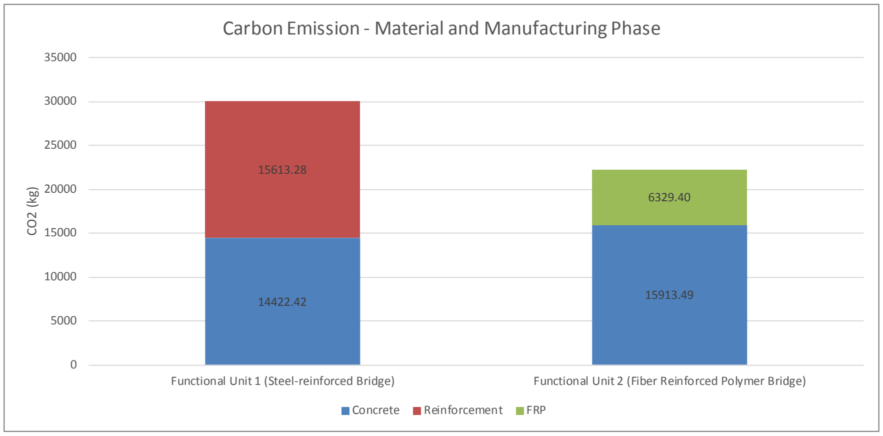

Figure 19: CO2 Emission of Material and Manufacturing Phase

EI of the construction phase includes both equipment used during construction and material transportation. Since the same equipment is used for two bridges construction, carbon emission produced during the time that equipment is used, is omitted. Transporting the materials to the plant, manufacturer and construction site has a significant impact on carbon emission, the carbon released during shipping is related to mass of materials, and the distance traveled and shipping methods used. Figure 20 compares carbon emitted during material transportation. In the phase, all materials are included in one section. FU-2 produces 9.17% more CO2 compared to FU-1.

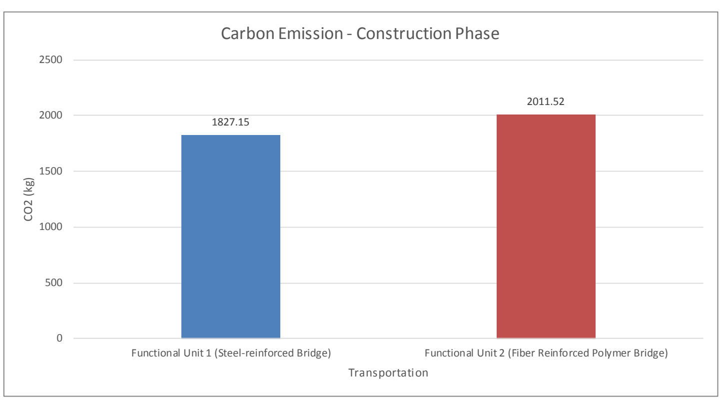

Figure 20: CO2 Comparison for the Construction Phase

The part, making carbon emission difference with regard to comparison of two functional unit, is shipping CFRP from Tokyo and 23661.63 km is made to transport it to the University of Miami construction site. Carbon emitted during use and maintenance phase of FU-1 is 18442.41 kg CO2 (Figure 21).

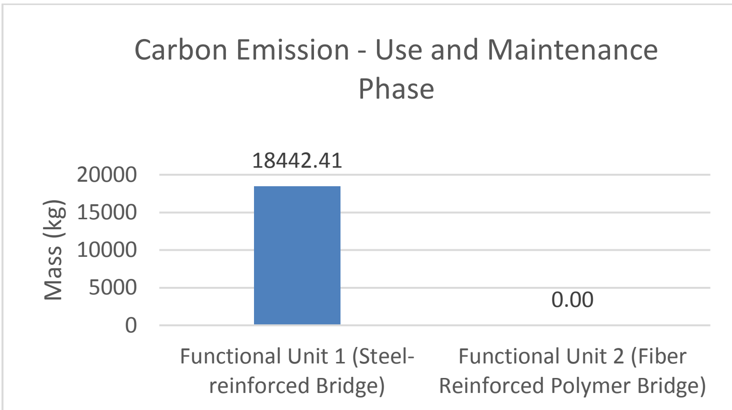

Figure 21: CO2 Emission Comparison for the Use and Maintenance Phase

End-of-life for FU-1 and FU-2 is estimated 80 years. Transportation emission data taken from 2016 and 2050 from MOVES software provide constant ratio for the EE and CO2 decrease per year. Therefore, FU-1 and FU2 end-of-life CO2 emission which stands for year 2096. Figure 22 demonstrates carbon emission through the end-of-life phase of both FUs. Carbon emission for FU-2 is 23.79 kg more than FU-1 due to concrete mass used.

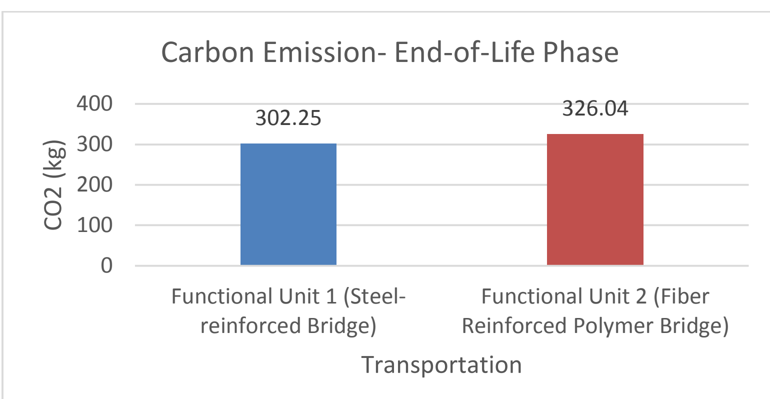

Figure 22: CO2 Emission Comparison for End-of-Life Phase

Figure 23 illustrates overall CO2 emission calculation based on initial case. Due to deck replacement of FU-1 during the given timeline, FU-1 has 26054.33 kg more CO2 emission compared to FU-2. Unit carbon emission and EE used for transportation during the deck replacement is used from year 2056.

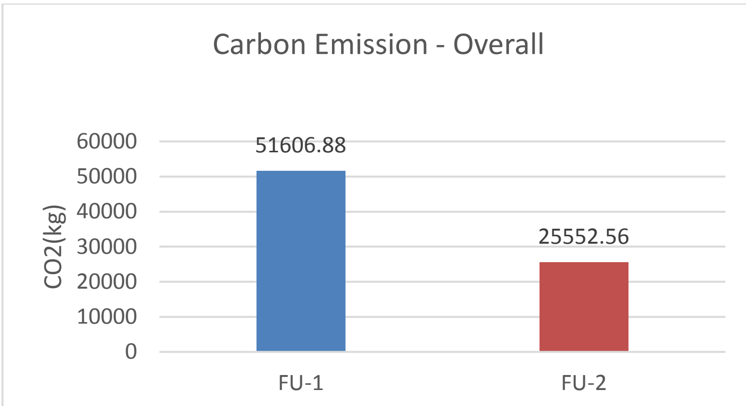

Figure 23: Overall CO2 Emission (Base Case)

Chapter 8

Alternative Scenarios

8.1 Using Recycled Steel Reinforcement for FU-1 (Scenario-1)

The study initially used virgin steel reinforcement for FU-1. However, FU-1 is the design alternative that is not built, thus possible EI must be considered. The EE and carbon emission differences between the usage of virgin and recycled steel reinforcement is calculated.

Material	Total Weight (kg)	Embodied Energy (MJ/kg)	Total Emb. Energy (MJ)	CO2/kg	Total CO2 (kg)
Steel Reinfrocement (Virgin)	5825.85	36.40	212061.02	2.68	15613.28
Steel Reinfrocement (Recycled)	5825.85	8.80	51267.50	0.42	2446.86

Table 15: Steel Reinforcement Comparison

Table15 shows the significant EI difference between using virgin and recycled material. During the usage of virgin steel reinforcement, EE is 36.40 GJ/km and if the recycled content is used, the value decreased by 27.5 GJ/km and 2.26 kg/km for carbon emission. Overall material carbon emission is decreased to 2446.86 kg from 15613.28 kg (Figure 24).

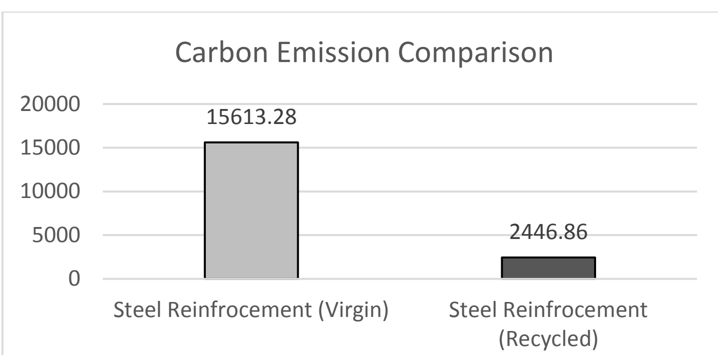

Figure 24: Virgin-Recycled Steel Reinforcement Carbon Emission Comparison

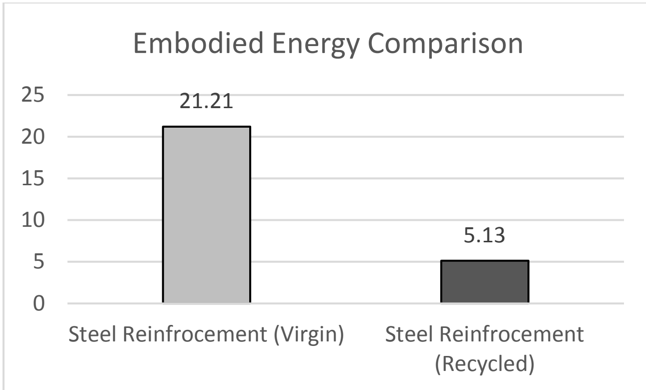

Figure 25: Virgin-Recycled Steel Reinforcement EE Comparison

Figure 25 shows that if the recycled steel reinforcement is used, there is 75.82% decrease in EE.

8.2 Predicted Service Life (Scenario-2)

Scenario-2 is based on predicted service life 65 year for FU-1 and 100 year for FU-2. End-of-life phase is conducted by reconstruction of FU-1 after completion of its life span. This scenario includes use and maintenance phase for both FUs. Figure 26 shows the time line of FU-1 and FU-2 for this scenario.

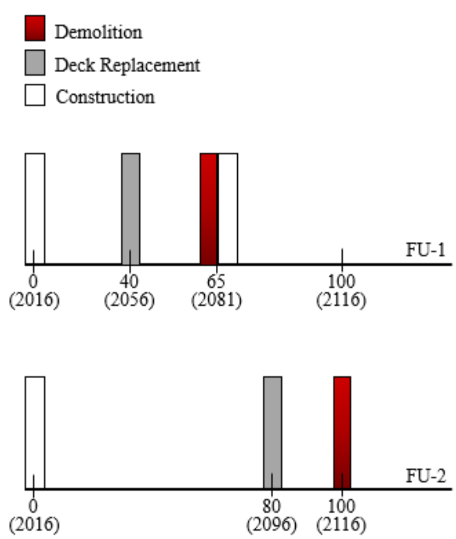

Figure 26: Timeline for Scenario 1

During the life-span of FU-2, FU-1 will require deck replacement in 2056 and in 2081 it will be demolished. Since the scenario based on total of 65 year service life for FU-1, FU-1 will be reconstructed in 2081.

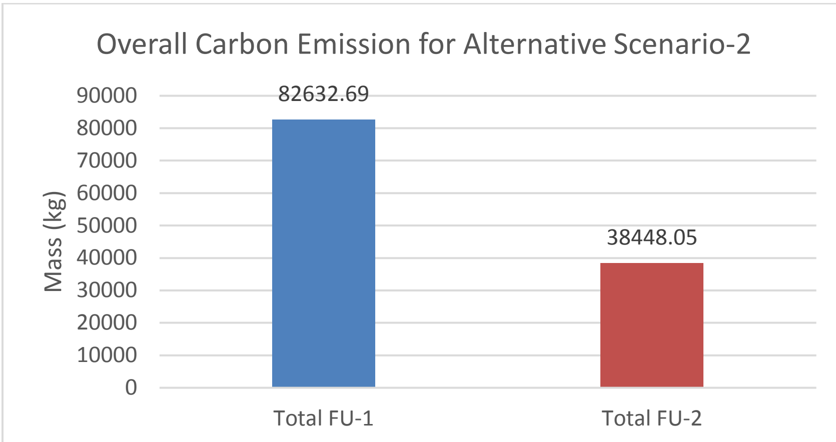

Figure 27: Total CO2 Emission for Scenario 1

Figure 27 indicates overall CO2 emission for this scenario. After FU-1 reaches the serviceable period, MOVES software data input is used for the demolition of the bridge in year 2081. The distance to move the materials to the landfill is assumed 34.92 km (21.7 miles). After demolition of the existing bridge, new FU-1 will be built after 65 years and Table 16 shows transportation methods and their carbon emission and EE.

		CO2 (kg/km)	EE (MJ/km)
2081	Single Unit Short-haul Truck	0.58	7.99
	Combination Short-haul Truck	1.03	14.14
	Combination Long-haul Truck	1.15	15.74

Table 16: Environmental Impacts for year 2059, (1 km = 0.621 miles)

EE and CO2 emission for FU-1 are calculated by considering one year EI resulted from each phase of LCA and multiplied by 35 years to evaluate total impact. It accounts for the years between the reconstruction of FU-1 and year 100 which is the given life span of FU-2.

FU-2 service life is predicted 100 years and total EI is summed up from materials and manufacturing, construction, use and maintenance, and end-of-life phases. Figure 28 demonstrates EE for both FUs for predicted life spans. Due to reconstruction needed for FU-1, overall EE is 551.47 GJ/km higher compared to FU-2.

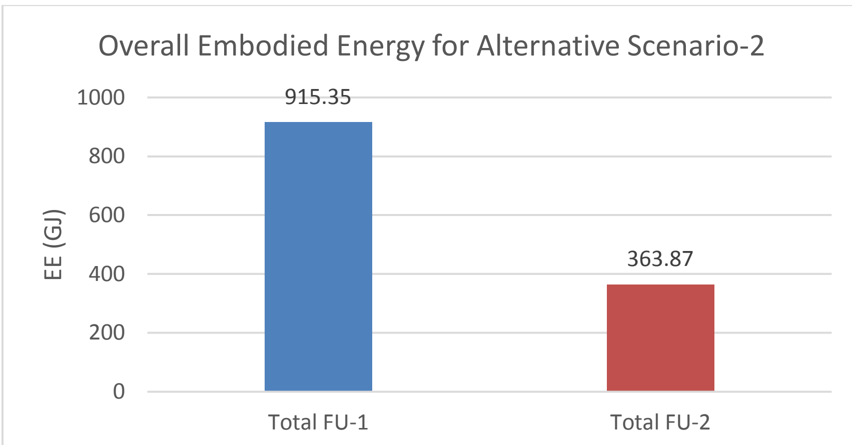

Figure 28: Total Embodied Energy for Scenario 1

8.3 Predicted Service Life (Scenario-3)

In this scenario, FU-1 service life will be 43 years. However, FU-2 life span will be considered as 75 years. In the scenario, both FUs do not require any maintenance. Figure 29 shows the timeline that is applied for scenario-3.

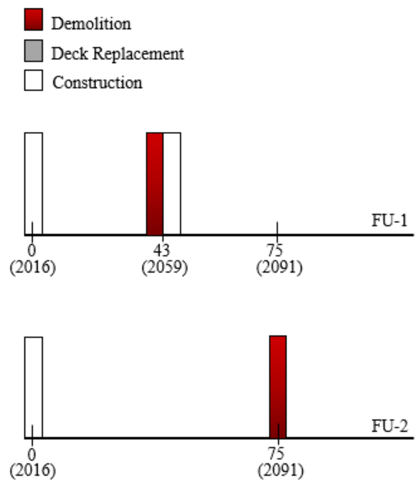

Figure 29: Timeline for Scenario 3

Carbon emission and EE calculations consist of material, construction, end of life which is year 2059 and demolition data for FU-1. EI of the years after the reconstruction of FU-1 through the end of life of FU-2 (year 2091) includes material, construction phase in 2059 and end of life phase in 2102.

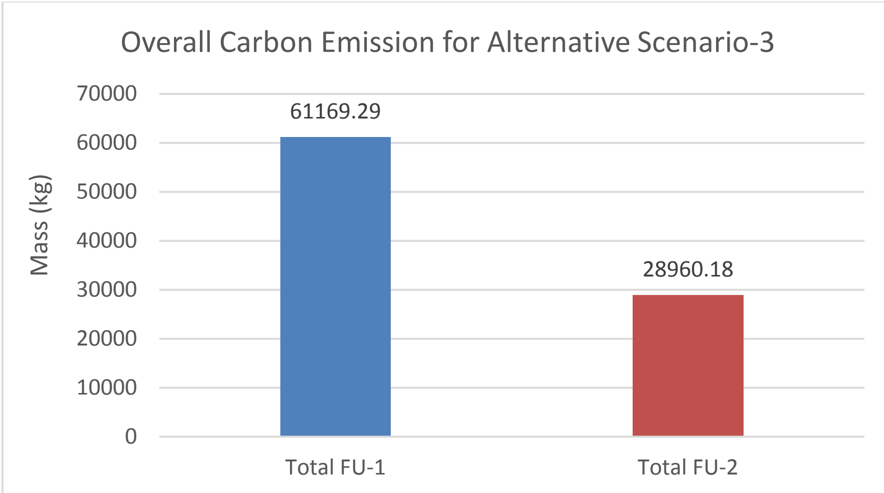

Figure 30: Total CO2 Emission for Scenario 2

Total CO2 emission is increased by 32209.11 kg for FU-1 due to the reconstruction of the structure (Figure 30). Figure 31 shows EE conducted by two FUs. It is shown that there is proportional increase in EE as CO2 emission and there is 254.76 GJ difference between FU-1 and FU-2.

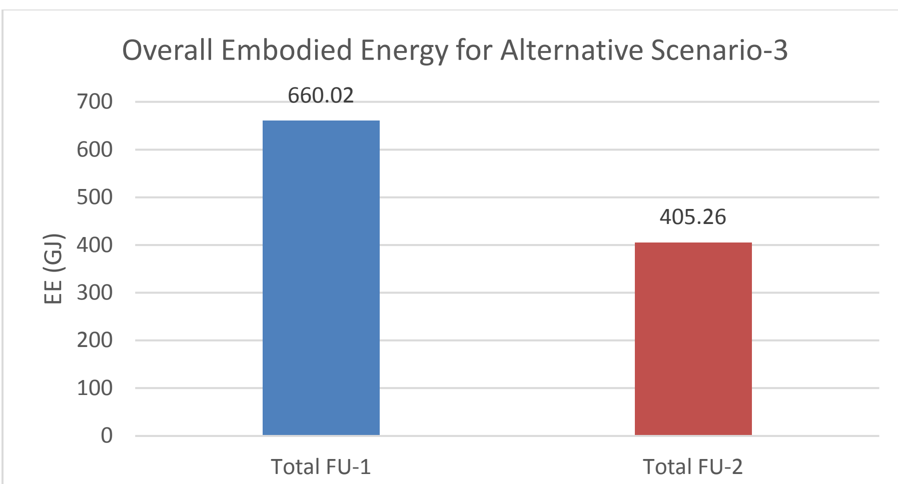

Figure 31: Total Embodied Energy for Scenario 2

Chapter 9

Critical Review

Critical review was supervised by three professors from Civil, Environmental and Architectural Engineering Department at University of Miami. The aim of the review was to conduct deeper view of the parameters used to compare two functional units, to verify the validity of inputs and outputs, to provide different approaches for the alternative scenarios. Critical review figured out that LCA methodology is applied accurately. However, there are more alternative methods that are needs to be conducted to the study. During critical review, three main approaches were considered to gain a deeper understanding of EI by considering these alternative concepts.

One of the aspects of critical review was to consider EI of mixed water which was used in the production of concrete for both functional units. Previously, EE data of water is taken from ICE and it is 0.2MJ/kg. However, it is hard to differentiate how the water is purified or mixed with other materials to produce new materials. Every application has its own requirements and ICE data provides water EE under miscellaneous section. Using seawater as concrete ingredient might be an option but there is limited data on how the seawater effects concrete quality and regarding EE of desalination if it is needed.

There are researches that studied usage of seawater in concrete mixture for the regions where the water has proper quality such as coastal areas or islands. According to the research, using seawater in concrete enhance durability and reduces carbon dioxide emission. Result shows that using sea water and unwashed sea sand concrete decreases

CO_2 by 40% compared to the structures using fresh water and land sand are transported from the mainland (Keisaburo Katano 2013).

Another recommendation was to provide two different end-of-life strategies that conduct variety of life span predictions for both functional unit during the critical review. One of these scenarios contributes that FU-1 will be assumed having 43 years of service life and FU-2 have 75 year. Second case pretends FU-1 with 43 years and FU-2 with 100-year life span. These two cases is discussed under alternative scenarios.

Lastly, possible recycled content of FRP reinforcement and its disposal methods were discussed and added to end-of-life phase.

Chapter 10

Discussion

The paper carried out the study comparing two concrete bridge structures by using LCA along with the cradle-to-grave method. Two structural systems differed from each other by their reinforcement and design variation. Both structures are made out of reinforced concrete. One of the system used traditional steel reinforcement embedded in concrete and it is named as FU-1. The other system, which is called FU-2, included selected alternative material to the steel reinforcement and used FRP reinforcement. Innovative material application induced design changes in FRP reinforced bridge and it caused increase in mass of concrete by is 10.34%. Total amount of concrete used for FU-1 is 113959.91 kg (125.62 tons) and for FU-2 125741.69 kg (138.61 tons).

Using FRP as a reinforcement instead of traditional steel provided significant decrease in total mass of reinforcement. Total weight of steel reinforcement is 5825.82 kg (6.42 tons) and 1900.72 kg (2.1 tons). Results support that, there is 3925.13 kg (4.33 tons) difference, which contributes 67.37% less than the mass of steel reinforcement due to its lightweight. Material and manufacturing phase shows that beside the structural design changes total weight of material used in construction, bringing alternative material solutions affects overall mass of system. Comparison done based on mass of material does not provide comprehensive results for overall EI. However, it indicated that there is a strong relationship between mass of materials and EI of the system.

Construction phase, contributing material transportation to the construction site and equipment used for site preparation and material placement, accounts for substantial part of EE and carbon emission. Motor Vehicle Emission Simulator comprises detailed equipment and vehicle types and ensures more accurate results for both EE and carbon emission. It is assumed that FU-1 uses streel rebar and the closest manufacturer is selected as supplier. On the other hand, actual manufacturers of FRP reinforcements used in the construction were provided. If the local manufacturers were preferred for FU-2, this would contribute having less carbon emission than FU-1.

FRP reinforced concrete bridges are relatively new applications and require long term analysis to enhance benefits. The limited data regarding similar applications, use and maintenance, and end-of-life phases need further research. To predict the service life of FRP Bridge is one of these limitations. Due to lack of long term data regarding the FRP reinforced concrete bridges' life span, three alternative scenarios based on different service life were studied to be able to increase the accuracy of the comparison. Because life span is a significant parameter that changes EI results due to its impact on maintenance needs for structures. During the maintenance phase, deck replacement causes an important increase on EI. Replacing deck contributes to enhance EI of material and manufacturing, construction and transportation.

Using recycled structural materials contribute less EI. The study calculated both virgin and recycled steel reinforcement carbon emission and EE. The results indicated that recycled content lower the EI.

Overall results show that, although FRP has recently taken a place in construction industry and needs long term research, it is an alternative approach to reduce EI of the system compared to traditional steel reinforced concrete structure.

Chapter 11

Conclusion

This paper provided comparative LCA for two bridge designs. The results demonstrated that material selection is a key contributor through the environmental performance of the bridge structures. Key variables that change the results of the study are; life span of the structures, mass of material, maintenance needs and material properties. Incorporating fiber reinforced polymer rebar to the bridge structure provided sustainable alternative to the conventional structural methods.

Following conclusions are drawn from the base case study:

- Application of FRP reinforcement in concrete bridge increased mass of concrete by 10.34% compared to traditional steel reinforced design
- Total reinforcement mass decreased by 67.37% by embedding FRP reinforcement to the system.
- Consumed EE and emitted carbon in the construction of FRP reinforced bridge throughout the LCA phases is less than steel reinforced bridge. Overall EE calculated for both FUs shows that, FU-1 has 556.86 GJ and FU-2 contributes 229.21 GJ.
- Overall CO2 emission from FRP reinforced bridge is 25552.56 (28.17 tons) and 51606.88 kg (56.87 tons) for steel-reinforced concrete bridge calculated based on predicted life span 80 year for FU-1 and FU-2. It contributes 50.49% decrease in carbon emission for the system whose EI was calculated based on LCA ISO14040 principles and framework.

Alternative scenarios resulted that life-span of the structures has significant impact on carbon emission and EE. Following results are reported from alternative scenarios:

- Alternative scenario-1 which used recycled steel reinforcement for FU-1 showed that there is 84.34% decrease in carbon emission and 75.82% in EE if the recycled steel reinforcement is used instead of virgin steel reinforcement.
- Alternative scenario-2 used 65 year predicted life span for FU-1 and 100 year for FU-2. Results demonstrated that due to less maintenance needed and its long service life, FU-2 overall carbon emission 46.52% and EE 39.75% is less than FU-1.
- Alternative scenario-3 was calculated based on 43 year predicted life span for FU-1 and 75 year for FU-2 without any maintenance requirement. As a result, overall FU-2 carbon emission is 47.34% less than FU-1 and EE is 61.40% less due to the reconstruction need of FU-1 to comply with the given service life for FU-2.

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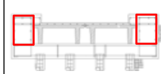
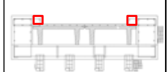
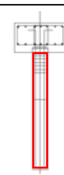
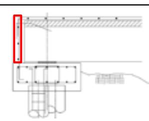
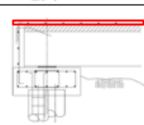
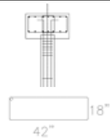
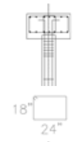
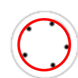
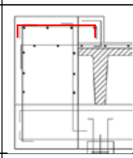
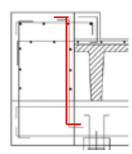
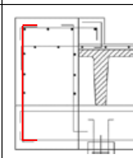
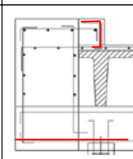
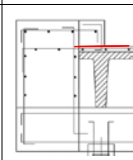
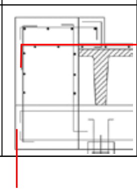
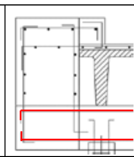
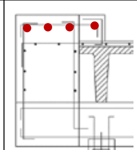
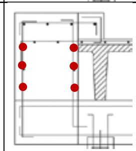
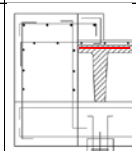
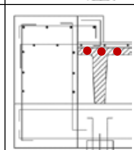
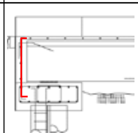
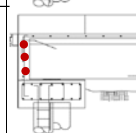
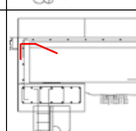
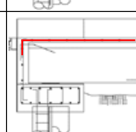
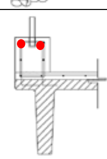
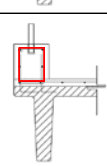
Appendix

Table A.1

Steel Reinforced Concrete Bridge (FU-1) Mass of Material Data

	Section	Type	Drawing	Quantity	sq.ft.	Length(ft)	Volume(ft3)
Concrete	1/S2.1	Girder		2	9.382	68.66	644.141
	1/S2.1	Solid Concrete at all four corners		4	44.389	4	177.555
	1/S2.2	Concrete Wall		2	2.722	70	190.554
	1/S2.3	Pile Cap		2	78.66	3.33	259.714
	A/S2.1	Augercast Pile		8	8.552	30	256.563
	2/S2.1	8" Concrete Wall		2	26.22	2.660	69.745
	2/S2.2	Deck		1	17.165	11.66	200.144

	Section	Type	Drawing	Quantity	Nominal Area(ft)	Length(ft)	Volume(ft3)	lb/ft
	A/S2.1	Augercast Pile Double #4		58	0.00139	9.219	0.743	0.668
	A/S2.1	Augercast Pile Double #4		58	0.00139	7.188	0.579	0.668
	4/S2.1	5#6		40	0.00305	32.083	3.914	1.502
	4/S2.2	17#3 @ 6"/ 20#3 @ 12"		296	0.000764	3.26	0.737	0.376
Reinforcement	1/S2.1	#4@8" or @10"		24	0.00139	4.52	0.1507872	0.668
	1/S2.1	#5@10"		20	0.00215	5.938	0.255334	1.043
	1/S2.1	#5@10"		20	0.00215	6.307	0.271201	1.043
	1/S2.1	#4@10"		20	0.00139	2.276	0.0632728	0.668
	1/S2.1	#3@8"		93	0.000764	16.33	1.16027916	0.376
	1/S2.1	#3@8"		12	0.000764	6.307	0.057822576	0.376

Reinforcement	1/S2.1	8#8 Top & Bottom		32	0.0548	20.197	35.4174592	2.67
	1/S2.1	#4@10"		8	0.00139	3.33	0.0370296	0.668
	1/S2.1	#5@10"		12	0.00215	3.33	0.085914	1.043
	1/S2.1	#4@6"		137	0.00139	11	2.09473	0.668
	1/S2.1	#3@6"		27	0.000764	68.094	1.404643032	0.376
	2/S2.1	#5@10"		28	0.00215	4.135	0.249	1.043
	2/S2.1	#5@10"		28	0.00215	13.3	0.801	1.043
	2/S2.1	#5		8	0.00215	3.115	0.054	1.043
	2/S2.1	#3@8"		21	0.000764	71.594	1.149	0.376
	3/S2.1	4#5		8	0.00215	62.094	1.068	1.043
	3/S2.1	#3 Ties @ 12"		124	0.000764	4.24	0.402	0.376

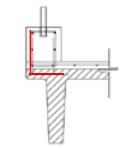
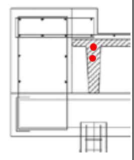
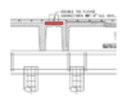
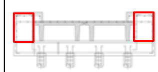
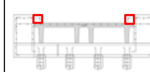
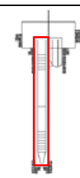
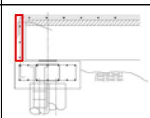
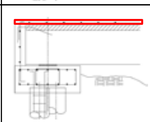
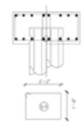
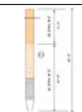
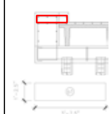
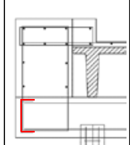
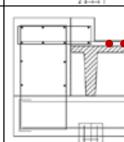
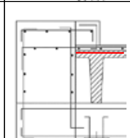
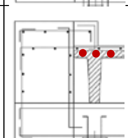
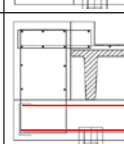
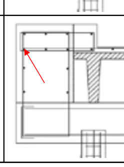
Reinforceme nt	3/S21	#4@12		248	0.00139	1.83	0.631	0.668
	1/S2.1	#6		36	0.00305	62.093	6.818	1.502
Double Tee Fl	1/S2.1			7	0.033	0.802	0.185	

Table A.2

FRP Reinforced Concrete Bridge (FU-2) Mass of Material Data

	Section	Type	Drawing	Quantity	sq.ft.	Length(ft)	Volume(ft3)
Concrete	1/S2.1	Girder		2	9.382	68.66	644.141
	1/S2.1	Solid Concrete at four corners		4	44.389	4	177.555
	1/S2.2	Curb		2	2.722	70	190.554
	1/S2.3	Pile Cap		2	78.66	3.33	255.403
	A/S2.1	Augercast Pile		8	11.170	40	446.804
	2/S2.1	8" Concrete Wall		2	26.220	2.66	69.745
	2/S2.2	Deck		1	17.165	11.66	200.144

	Section	Type	Drawing	Quantity	Nominal Area(ft)	Length(ft)	Volume(ft3)	lb/ft
	A/S2.1	Augercast Pile Cap Double #4		100	0.00139	6.49	0.902	0.220
	4/S2.1	6#6		48	0.00305	40.01	5.857	0.494
	4/S2.1	28#3 @ 6"/ 20#3 @ 12"		384	0.000764	2.46	0.722	0.132
	1/S2.1	#4@8"		24	0.00139	9.67	0.323	0.220
	1/S2.1	#5@8"		40	0.00215	15.75	1.355	0.465
Reinforcement	1/S2.2	#4		32	0.00139	3.67	0.163	0.220
	1/S2.1	#4@1'		11	0.00139	69.26	1.059	0.220
	1/S2.1	#4@6"		137	0.00139	11	2.09473	0.22
	1/S2.1	#3@6"		27	0.000764	68.094	1.404643032	0.132
	1/S2.1	#4@6"		32	0.0548	18.948	33.227	0.881
	1/S2.1	4#4 Top & Bottom		32	0.00139	3.33	0.148	0.220

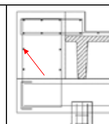
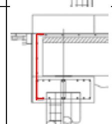
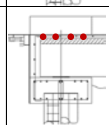
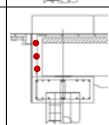
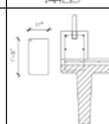
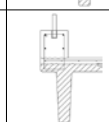
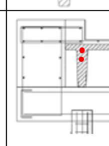
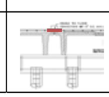
	1/S2.1	2#4 Left & Right		16	0.00139	3.33	0.074	0.220	
	2/S2.1	#5@8"		40	0.00215	7.5	0.645	0.287	GFRP
Reinforcement	2/S2.1	#3@8"		110	0.000764	13.3	1.118	0.132	
	2/S2.1	#5@8"		16	0.00215	13.3	0.458	0.465	
	3/S2.1	#4 Ties @ 12"		124	0.00139	4.67	0.805	0.220	
	3/S2.1	4#5		8	0.00215	62.094	1.068	0.465	
CFRP	1/S2.1	#6		36	0.00194	62.093	4.337	0.249	CFRP
Double Tee Flange	1/S2.1			7	0.033	0.802	0.185		

Table B.1

FU-1 and FU- Transportation Data

	Materials	Location	Distance (miles)	Distance (km)	Address
Steel	Rebar	Jacksonville, FL (Gerdau Plant)	394	634.08	16770 Rebar Road, Jacksonville, FL 32234
	Cement to Plant	Medley,FL (Pennsuco Plant)	14	22.53	Pennsuco Cement Co LLC, 11000 NW 121st Way, Medley, FL 33178
	Sand to Plant (Concrete)	Center Sand,Clermont	257	413.60	16375 Hartwood Marsh Rd, Clermont, FL 34711
	Sand to Plant (Double Tee)	Center Sand,Clermont	247	397.51	16375 Hartwood Marsh Rd, Clermont, FL 34711
	Aggregates to Plant	Medley,FL (Pennsuco Plant)	14	22.53	Pennsuco Cement Co LLC, 11000 NW 121st Way, Medley, FL 33178
	Fly Ash to Plant (Concrete)	Jacksonville	360	579.36	Separation Technologies LLC, 11201 New Berlin Rd, Jacksonville, FL 32226
	Fly Ash to (Double Tee)	Jacksonville	352	566.49	Separation Technologies LLC, 11201 New Berlin Rd, Jacksonville, FL 32226
	Ready-mixed to UM	South Miami Titan Ready-Mix	3	4.83	7355 SW 48th St Miami, FL 33155
	Concrete Mix to Coreslab	Medley,FL (Pennsuco Plant)	0.7	1.13	Pennsuco Cement Co LLC, 11000 NW 121st Way, Medley, FL 33180
	Double Tee Precast	Medley,FL (Coreslab Structures)	17.6	28.32	Coreslab Structures Inc, 10501 NW 121st Way, Medley, FL 33178
	Double Tee Flange	Miami,FL	10.3	16.58	C & R Metals, Inc., 2991 NW North River Dr, Miami, FL 33142
FRP	BFRP	Pompano Beach	59.8	96.24	NO RUST REBAR INC., 2681 NE 4th Ave, Pompano Beach, FL 33064
	CFRP	Tokyo-Miami	14702.69	23661.63	Tokyo Rope Manufacturing Co.,Ltd., Tokyo, JP
	GFRP	Seward, NE	1777	2859.80	Hughes Brothers Inc, 210 N 13th St, Seward, NE 68434
	Cement to Plant	Medley,FL (Pennsuco Plant)	14	22.53	Pennsuco Cement Co LLC, 11000 NW 121st Way, Medley, FL 33178
	Sand to Plant (Concrete)	Center Sand,Clermont	257	413.60	16375 Hartwood Marsh Rd, Clermont, FL 34711
	Sand to Plant (Double Tee)	Center Sand,Clermont	247	397.51	16375 Hartwood Marsh Rd, Clermont, FL 34711
	Aggregates to Plant	Medley,FL (Pennsuco Plant)	14	22.53	Pennsuco Cement Co LLC, 11000 NW 121st Way, Medley, FL 33178
	Fly Ash to Plant (Concrete)	Jacksonville	360	579.36	Separation Technologies LLC, 11201 New Berlin Rd, Jacksonville, FL 32226
	Fly Ash to (Double Tee)	Jacksonville	352	566.49	Separation Technologies LLC, 11201 New Berlin Rd, Jacksonville, FL 32226
	Ready-mixed to UM	South Miami Titan Ready-Mix	3	4.83	7355 SW 48th St Miami, FL 33155
	Concrete Mix to Coreslab	Medley,FL (Pennsuco Plant)	0.7	1.13	Pennsuco Cement Co LLC, 11000 NW 121st Way, Medley, FL 33180
	Double Tee Precast	Medley,FL (Coreslab Structures)	17.6	28.32	Coreslab Structures Inc, 10501 NW 121st Way, Medley, FL 33178
	Double Tee Flange	Miami,FL	10.3	16.58	C & R Metals, Inc., 2991 NW North River Dr, Miami, FL 33142

Table B.2

Vehicle Emissions and Embodied Energy (U.S. EPA MOVES (2010b) 2010)

	yearID	pollutantID	sourceTypeID	fuelTypeID	modelYearID	emissionQuant	activity	emissionRate	massUnits	energyUnits	distanceUnit
2016	2016	90	52	2	2016	7885275.5	11962.11914	659.1871731	grams	joules	km
	2016	90	61	2	2016	8074931	7263.751465	1111.675012	grams	joules	km
	2016	90	62	2	2016	18759082	15285.50098	1227.24679	grams	joules	km
	2016	91	52	2	2016	1.07048E+11	11962.11914	8948916.866	grams	joules	km
	2016	91	61	2	2016	1.09623E+11	7263.751465	15091749.06	grams	joules	km
	2016	91	62	2	2016	2.54667E+11	15285.50098	16660717.09	grams	joules	km
2050	2050	90	52	2	2050	9196627	14772.82422	622.5368192	grams	joules	km
	2050	90	61	2	2050	12347330	11491.47266	1074.477603	grams	joules	km
	2050	90	62	2	2050	34300180	28776.56641	1191.948321	grams	joules	km
	2050	91	52	2	2050	1.2485E+11	14772.82422	8451352.158	grams	joules	km
	2050	91	61	2	2050	1.67623E+11	11491.47266	14586759.17	grams	joules	km
	2050	91	62	2	2050	4.65649E+11	28776.56641	16181534.73	grams	joules	km

Table B.3

Truck Type and Years Used for Construction, Maintenance and End of Life Phases

		CO2 (kg/km)	EE (MJ/km)
2016	Single Unit Short-haul Truck	0.66	8.95
	Combination Short-haul Truck	1.11	15.09
	Combination Long-haul Truck	1.23	16.66

		CO2 (kg/km)	EE (MJ/km)
2056	Single Unit Short-haul Truck	0.61	8.32
	Combination Short-haul Truck	1.06	14.46
	Combination Long-haul Truck	1.18	16.03

		CO2 (kg/km)	EE (MJ/km)
2059	Single Unit Short-haul Truck	0.61	8.32
	Combination Short-haul Truck	1.06	14.46
	Combination Long-haul Truck	1.18	16.03

		CO2 (kg/km)	EE (MJ/km)
2081	Single Unit Short-haul Truck	0.58	7.99
	Combination Short-haul Truck	1.03	14.14
	Combination Long-haul Truck	1.15	15.74

		CO2 (kg/km)	EE (MJ/km)
2091	Single Unit Short-haul Truck	0.57	7.85
	Combination Short-haul Truck	1.02	13.99
	Combination Long-haul Truck	1.14	15.60

		CO2 (kg/km)	EE (MJ/km)
2096	Single Unit Short-haul Truck	0.56	7.77
	Combination Short-haul Truck	1.02	13.92
	Combination Long-haul Truck	1.13	15.48

		CO2 (kg/km)	EE (MJ/km)
2116	Single Unit Short-haul Truck	0.54	7.48
	Combination Short-haul Truck	0.99	13.62
	Combination Long-haul Truck	1.11	15.25

Table B.3

Maintenance Data for FUs

	Vehicle	Fuel Type	Total Weight(kg)	Vehicle Capacity(kg)	Number of Trucks	Distance(km)	Distance+Return(km)	Total Distance (km)	CO2 (kg/km)	EE (GJ/km)	CO2 (Kg)	EE (GJ)
Functional Unit 1 (Steel-reinforced Bridge)	Dump Truck (Rebar)	Diesel	2821.46	15875.73	0.1777	634.08	1268.16	225.38	1.18	0.0160	265.16	3.61
	Concrete Truck (Ready Mix from South Mi	Diesel	12682.48	15875.73	0.7989	4.83	9.66	7.71	0.61	0.0083	4.69	0.06
	Semi-Trailer (Double Tee)	Diesel	0.00	15875.73	0.0000	28.32	56.65	0.00	0.61	0.0083	0.00	0.00
	Concrete Truck for Cement (Pennsuco to S	Diesel	2514.94	15875.73	0.1584	22.53	45.06	7.14	0.61	0.0083	4.34	0.06
	Concrete Truck for Sand (Center Sand to S	Diesel	3981.03	15875.73	0.2508	413.60	827.20	207.43	1.06	0.0145	220.07	3.00
	Concrete Truck for Aggregate (Pennsuco t	Diesel	5178.26	15875.73	0.3262	22.53	45.06	14.70	0.61	0.0083	8.94	0.12
	Concrete Truck for Sand (Center Sand to P	Diesel	0.00	15875.73	0.0000	397.51	795.01	0.00	1.06	0.0145	0.00	0.00
	Concrete Truck (Pennsuco Ready Mix to C	Diesel	0.00	15875.73	0.0000	1.13	2.25	0.00	0.61	0.0083	0.00	0.00

					2096							
	Vehicle	Fuel Type	Total Weight(kg)	Vehicle Capacity(kg)	Number of Trucks	Distance(km)	Distance+Return(km)	Total Distance (km)	CO2 (kg/km)	EE (GJ/km)	CO2 (Kg)	EE (GJ)
Functional Unit 2 (Fiber Reinforced Polymer Bridge)	Medium Duty Truck (BFRP)	Diesel	424.09	15875.73	0.0267	96.24	192.48	5.14	0.56	0.0078	2.88	0.04
	Pickup Truck (CFRP)	Diesel	252.47	15875.73	0.0159	15.64	31.29	0.50	0.56	0.0078	0.28	0.00
	Concrete Truck (Ready Mix from South Mi	Diesel	12682.48	15875.73	0.7989	4.83	9.66	7.71	0.56	0.0078	4.32	0.06
	Semi-Trailer (Double Tee)	Diesel	0.00	15875.73	0.0000	28.32	56.65	0.00	0.56	0.0078	0.00	0.00
	Concrete Truck for Cement (Pennsuco to S	Diesel	2514.94	15875.73	0.1584	22.53	45.06	7.14	0.56	0.0078	4.00	0.06
	Concrete Truck for Sand (Center Sand to S	Diesel	3981.03	15875.73	0.2508	413.60	827.20	207.43	0.56	0.0078	116.16	1.61
	Concrete Truck for Aggregate (Pennsuco t	Diesel	5178.26	15875.73	0.3262	22.53	45.06	14.70	1.02	0.0139	14.99	0.20
	Concrete Truck for Sand (Center Sand to P	Diesel	0.00	15875.73	0.0000	397.51	795.01	0.00	0.56	0.0078	0.00	0.00
	Concrete Truck (Pennsuco Ready Mix to C	Diesel	0.00	15875.73	0.0000	1.13	2.25	0.00	1.02	0.0139	0.00	0.00
	Maritime	Diesel	252.47	1.00	-	23636.46	47272.91	47272.91	0.56	0.01	465.46	1.91