

Life Cycle Assessment: Comparing Glass Fiber Reinforced Polymer Facade Panels to
Precast Concrete Facade Panels Including Secondary Structural Effects

Commissioned by:

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CEE226: Life Cycle Assessment for Complex Systems

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Abstract

Kreysler & Associates is a prominent manufacturer of fiber reinforced polymer (FRP) facade panels, and they have commissioned a study to examine the cost and life cycle impact reduction of changing the facade type on a building from precast concrete (PCC) to glass fiber reinforced polymer (GFRP). For this study, a representative sample building has been chosen to examine these effects; this building is a 7-story hotel located in Anaheim, CA.

An important concept with the analysis is the impact that light weighting the facade has on the steel required for the structure. The chosen building uses an ETABS structural model to examine the effects of different loading cases, given live, dead and lateral loading for earthquakes. To examine structural changes, both facades were added to the building as a line load and the amount of extra steel was calculated. A building with a concrete facade uses 1.32 times as much steel compared to the GFRP facade.

Overall, a building with a GFRP facade has 39% less life cycle impact (LCI) than a building with a PCC facade when compared with a single point indicator using SimaPro. As expected, steel is the main contributor to the impact of both buildings due to the large amount required and the reliance on natural resource (iron) used to make steel. This impact still holds even when varying the amount of recycled steel used in a building. Comparing just the facade panels also shows that concrete materials create more impact than GFRP. This is due to the higher material requirement and the impact of cement production and transportation. Concrete also uses a large amount of water that is a significant contributor to the overall impact of facade panel manufacturing.

The extreme difference in weight also causes a large difference in the impact of transportation for the project. GFRP is trucked from a longer distance away but with a lighter weight the number of ton-miles will be managed. PCC panels are produced closer to the site but have more mass which creates similar number of ton-miles. Trucking for steel materials follows the same principles; a reduction in steel will create less impact from truck use and lessen the cost of the building from material transportation.

GFRP and PCC panels have been designed so that they have an equivalent R-Value of 19.8. Using panels with equivalent values ensures the use phase of the building will be the same for both cases and not make an impact on this analysis. Since LCA studies are subject to assumptions and sensitivity, different cases have been considered for both materials. Comparisons between materials at different sensitivities have shown the study conclusions are robust to variations in materials.

Overall this study has shown that by switching the facade for this specific building, a cost savings of \$1,248,223 and an overall lessening of life cycle impacts is achieved. Next steps for this study can be expanded to a more general case to examine buildings in other locations to determine the sensitivity of impact lessening on different sizes and types of buildings.

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Introduction

Kreysler & Associates is seeking to compare the life cycle costs and impacts of their Glass Fiber Reinforced Polymer (GFRP) panels with precast concrete panels and to determine the secondary effects of their lightweight GFRP panels on the structural steel members. The company would like to prove to their existing and future clients that their GFRP panels are a more sustainable option than precast panels, both from economic and environmental standpoints.

To conduct this study, GFRP sandwich panels manufactured by Kreysler and precast sandwich panels manufactured by Clark Pacific have been selected as facades for a 7-story building with a structural steel frame, which will serve as a functional unit for this project. The facade will be made up of 600 panels, each of which will be 14 ft wide, 9.5 ft high, and 8.15 in thick.

GFRP panels will be manufactured at Kreysler's American Canyon, CA facility and transported by truck to the project site in Anaheim, which is 416.5 miles from the plant. In contrast, the manufacture of precast panels will take place in Clark Pacific's Adelanto plant and the transport will cover 82.4 miles.

The life cycle assessment of the two panel types was conducted using SimaPro 8.0. For all analysis in SimaPro the BEES+ V4.04 / USA per cap '97-EPA Weighting method was used. The life cycle costs are calculated using the data provided by Bill Kreysler as well as the industry rates for steel and trucking.

Goal and Scope

Purpose of this Life Cycle Assessment (LCA) Study

This LCA study was undertaken to compare the environmental impacts of a steel structure building with two different cladding systems: one with GFRP sandwich panels and the other with precast concrete sandwich panels. A sandwich panel consists of an exterior layer of the cladding material, an insulating material of Polyisocyanurate foam insulation and an interior layer of the cladding material. The project used for the study is a real project in the design phase, but all analysis of this study is for theoretical proof of concept and will not be implemented. Various assumptions have been made in order to carry out a simplified LCA.

Comparing the two structures can prove to be useful for Kreysler & Associates and their clients when they are faced with choosing between Kreysler's product, i.e. the FRP panels, and other alternatives. For instance, the San Francisco Museum of Modern Art chose FRP facade panels over GFRC panels for the building's exterior envelope. Additionally, this study aims to provide the decision makers with general facts and key figures about comparison of the two structures with GFRP panels and precast concrete panels. For these purposes, the audience of this report includes decision makers and engineers who engage in building design and construction as well as manufacturers of facade panels of various materials. The results of the study significantly depend upon the assumptions made regarding the design of both structures. It should be acknowledged that for this study, it is not feasible to come up with any typical steel structure enclosed with any typical FRP or precast concrete sandwich panels. Therefore, it is strongly recommended that engineers and designers take into consideration the structure's location and other economic and cultural factors when making decisions during the design process.

Selections of the design of the structures as well as the two compared sandwich panels were made after consulting with Professor Michael Lepech from Stanford University and Bill Kreysler from Kreysler & Associates. Mr. Kreysler provided various information and data regarding the production and prefabrication of his company's GFRP panels. Material databases within SimaPro were used for quantifying impacts while RS Means was used to perform productivity estimating for building erection.

Functional Unit

The functional unit chosen for the purpose of this study is a 7-story building located in Anaheim, California, constructed from a steel frame structure and covered in 600 identical exterior sandwich panels. Each story is 9.5 feet tall with the perimeter ranging from 744 feet to 1381 feet. An architectural rendering of the selected building can be seen in Appendix A.

System Boundaries

The following LCA has been simplified, taking into account the production and transportation of materials, and end-of life. The construction costs of both structures have been included in the construction phase. The operation and maintenance period and the environmental impacts linked to the construction processes have been scoped out of this study. It is important to note this study does not consider other insignificant processes during construction such as geotechnical survey, construction site mobilization, manufacturing of machinery, equipment, and vehicles, and the environmental impacts associated with the construction workers on site.

DESIGN AND TECHNICAL DETAILS OF THE STRUCTURES

Building Structure

The building structure consists of a composite structure: a steel structural frame and concrete filled metal decks. The steel structure is comprised of type W beams and HSS columns. The concrete filled metal decks of both structures are assumed to be similar. As a result, they have been excluded from the study.

The building structure was analyzed with loads such as live loads, dead loads, wind loads, and earthquake loads according to California's regulation. Since the function of adding cladding to the building in ETABS is considered zero self-weight, the panels added to the LCA study were represented by line loads adding directly on the W beams instead.

GFRP Panels

The GFRP sandwich panels consist of 3/16 inches thick front and back GFRP skins filled by a 3-in core material layer, also served as insulation. The thickness of the core material was chosen so that an R-value of 19.8 F.sqft.hr/Btu could also be achieved. (Archtoolbox, 2018)

Precast Concrete Panels

This study has considered 2/ 3.15/ 3 panels that each comprises a 2-in.-thick concrete layer, a 3.15-in.-thick insulation layer, and a 3-in.-thick concrete layer. In reality, most sandwich panels are designed to be as thin as possible. In this particular LCA study, the panel thickness is determined strictly by the final desired thermal resistance R-value of 19.8 F.sqft.hr/Btu. (Archtoolbox, 2018)

SECONDARY-STRUCTURAL IMPACT COMPARISON

Since the weight of the panel cladding outside of a building may influence the amount of steel used in its structural frame, which could further impact the LCA process of the whole building, the LCA study analyzed the model with different types of panel to compare the impact on its structure.

According to the ETABS analysis, the total amount of steel used when adding the GFRP is just under 1,600 ton. However, adding the precast panels with a density of 150 pcf to the same structural model would cause around 3,000 elements to fail in its structural frame. Therefore, with 150 pcf precast panels, the building would need 1.32 times more structural steel than GFRP panels to withstand the loads such as live load, dead load, and earthquake load; for 120 pcf precast panels, the structural model would need 1.18 times more structural steel to withstand all the exterior loads; for 90 pcf precast panels, the ratio would decrease to 1.12.

Table 1: Steel Ratio vs. Concrete Density

Type of Facade	Panel Weight (lbs)	Total Amount of Steel (ton)	Ratio compared to GFRP
GFRP	149.63	1598.9	-
150 pcf Precast Panel	8402.55	2111.0	1.32
120 pcf Precast Panel	6740.05	1886.9	1.18
90 pcf Precast Panel	5077.55	1790.8	1.12

LIMITATIONS AND ASSUMPTIONS

An assumption made on the structural analysis for this project is that the live loads, dead loads, wind loads, and earthquake loads are added to our structural frame according to California's regulation. For specific location-based applications of this study, a more detailed structural analysis will need to be performed with the applicable local design code. For example, buildings in northern climates may include snow loading cases which could change the benefits of using a lighter facade when compared to the analysis performed using the California structural code.

In addition, the panel was added onto the structure frame right on the W beam, which means that the weight of the panel is being supported by the structural frame instead of supporting itself in the scenario of cladding outside the building.

Assessing the environmental impacts of the construction erection phase for such a structure has been a challenging task of this LCA. The production rates data linked to the operating hours of construction equipment and machine depends on each construction company and can vary from one contractor to another. This information is typically private and not available for students to access. Additionally, the operation and use phases are not well documented and not readily accessible to students.

PROCESS FLOW DIAGRAMS

GFRP Panels

The process flow diagram for GFRP panels can be found in Appendix B. Materials for GFRP are transported from suppliers at different locations throughout North America. Main material components include resin, gel coat and glass fiber as these are the main structure creating compounds within GFRP. The forming process takes place in steel forms with a vacuum curing process to ensure proper density, strength and finish. After curing, attachment hardware is bonded to the panels before they are transported to the construction site for the building erection process.

Precast Panels

The process flow diagram for PCC panels can be found in Appendix B. Materials considered during analysis were concrete (cement, water and aggregate), reinforcing mesh, rigid foam insulation, and release agent. The metal formworks are excluded from consideration as they can be reused over and over. In terms of life cycle, 100% of precast panels goes into the landfill at their end-of-life stage. Other process flow considerations include transportation of materials to the manufacturing facility and transportation of completed panels to the site for installation.

Structural Steel

The process flow diagram for structural steel can be found in Appendix B. Structural steel for buildings generally consists of HSS and W-Sections created using a hot extrusion process. The steel represented in this building project will be 90% recycled and come from American sources. Iron ore and lime are major components of carbon steel and through heating and extrusion they are turned into engineered sections for use in building construction. Steel as with other materials is also transported twice, once to the manufacturing facility and once from the facility to the site for erection.

Inventory

GFRP Panels

Glass Fiber Reinforced Polymer (GFRP) is a lightweight building material that is being used in modern facade building. It is generally made into sandwich panels which consist of an insulation panel surrounded by two double layers of resin based GFPR. This material combination creates a facade that has weather resistance and insulation that compare to all conventional materials.

The GFRP layers are mainly made up of resin, gel coat and glass fiber. These materials create the structure and strength for the composite panel. The remaining lesser materials consist of filler materials and activation chemicals to complete and harden the mixture. The forming process also includes a vacuum curing method; the energy of the pump and the nylon curing bags have also been included.

GFRP is always made in a form to ensure uniform shape; for this analysis the formwork used is steel which means that it can be reused indefinitely. For this reason, the impact contribution to each panel has been excluded. Table 2 below shows all included materials and the manner in which they have been represented in the SimaPro analysis program.

Table 2: GFRP Panel Inventory and Representations

Process Flow Material	SimaPro Representation	Amount
Transportation to Facility	Transport, Freight Train	68,530 tmi
Resin	Polyester Resin	2.54 ton
Gel Coat	Polyester Resin + Plaster Mixing	2.54 ton
Glass Fiber	Glass Fiber	8.16 ton
Insulation Core	Polyurethane, Rigid Foam	22.7 ton
Plexus	Methyl Methacrylate	0.962 ton
Methyl-Ethyl Ketone Peroxide (MEKP)	Hydrogen Peroxide	0.362 ton
Alumina Trihydrate (ATH)	Aluminum Oxide	3.63 ton
Sand Blasting Sand	Silica Sand	0.200 ton
Vacuum Bag	Nylon 6+Extrusion, Plastic Film	0.330 ton
Steel Hardware	Steel, Chromium Steel 18/8	6.0 ton
Transportation to Site	Transport, Combination Truck	18,444.5tmi
Transportation to Disposal	Transport, Combination Truck	3,000tmi

Materials chosen in SimaPro represented the closest available representation to the regular material. When the actual material was not available, the closest available material by chemical structure was chosen for the representation. This was the case for both MEKP and ATH which are unique compounds that can generally be grouped into chemical families that exist within SimaPro.

PCC Panels

The life cycle of precast concrete (PCC) panels follows a cradle-to-grave system, with all the panels being disposed of at the end of their service life. Three phases are considered for the life cycle of concrete panels. The first phase is the production and transport of materials needed for the precast panels, including concrete, steel, and rigid foam insulation. In this phase, the inputs are the raw materials needed such as cement, sand, water, crushed rock, and reinforcing steel while the outputs are the finished materials that go into the manufacture of precast panels and the emissions associated. The second phase is the transport of the panels to the site while the last phase is their disposal. As is the case with GFRP panels, the use phase of the building is excluded from consideration by ensuring both panel types have the same R-value of 19.8.

Table 3 shows the SimaPro representation for the materials in the process flow diagram of precast panels.

Table 3: PCC Panel Inventory and Representations

Process Flow Material	SimaPro Representation	Amount
Transport to Facility	Transport, Freight Train	141,249 tmi
Cement	Cement, Portland	340.1 ton
Water	Water, tap water	453.4 ton
Aggregate	Gravel, Crushed	1,133.5 ton
	Sand	340.1 ton
Insulation Foam	Polyurethane, Rigid Foam	23.8 ton
Steel Wire Mesh	Reinforcing Steel	10.9 ton
Steel Attachment Hardware	Steel, Chromium Steel 18/8	6.82 ton
Transport to Site	Transport, Combination Truck	46,713.7 tmi

Steel

In order to implement the goal of sustainability, approximately 90% of the steel material used in this building structure comes from recycled scrap collection, based on the estimation by AISC that steel has a recovery rate of 98%, in which 92% can be reproduced as steel product (98% x 92%= 90%). Using recycled steel can reduce 75% of energy, 86% of emissions to air, 40% of process water, and 97% of mining and transportation required for the production of virgin steel (American Institute of Architects' Environmental Resource Guide). Based on the data and regulations provided by AISC, US Energy Information Administration (EIA), US Geological Survey (USGS), and the selected steel suppliers, the following materials/assembles and processes are required for the steel structure in this study: Table 4 below shows the SimaPro representation for the materials in the life cycle flow diagram of steel.

Table 4: Steel Inventory and Representations

Process Flow Material	SimaPro Representation	Amount
Transportation to Facility	Rail Transport, diesel driven	598,666 tmi
Iron Ore	Iron Scrap, Sorted, pressed	1,439 ton
Flux and Lime		
Pellets		
Fossil PCI		
Oxygen		
Sinter	Natural gas and Combustion of Natural	Supply 0.411 ton

Process Flow Material	SimaPro Representation	Amount
Coke	Gas	Combustion 12.6 GJ
Blast Furnace Gas		
Process Water	Process Water, Ion Exchange, At Plant	363.6 ton
Post Consumer Scrap	Steel Section including recycling	159.9 ton
Transportation to Site	Transport, Combination Truck	39,000 tmi

LIFE CYCLE IMPACT ASSESSMENT

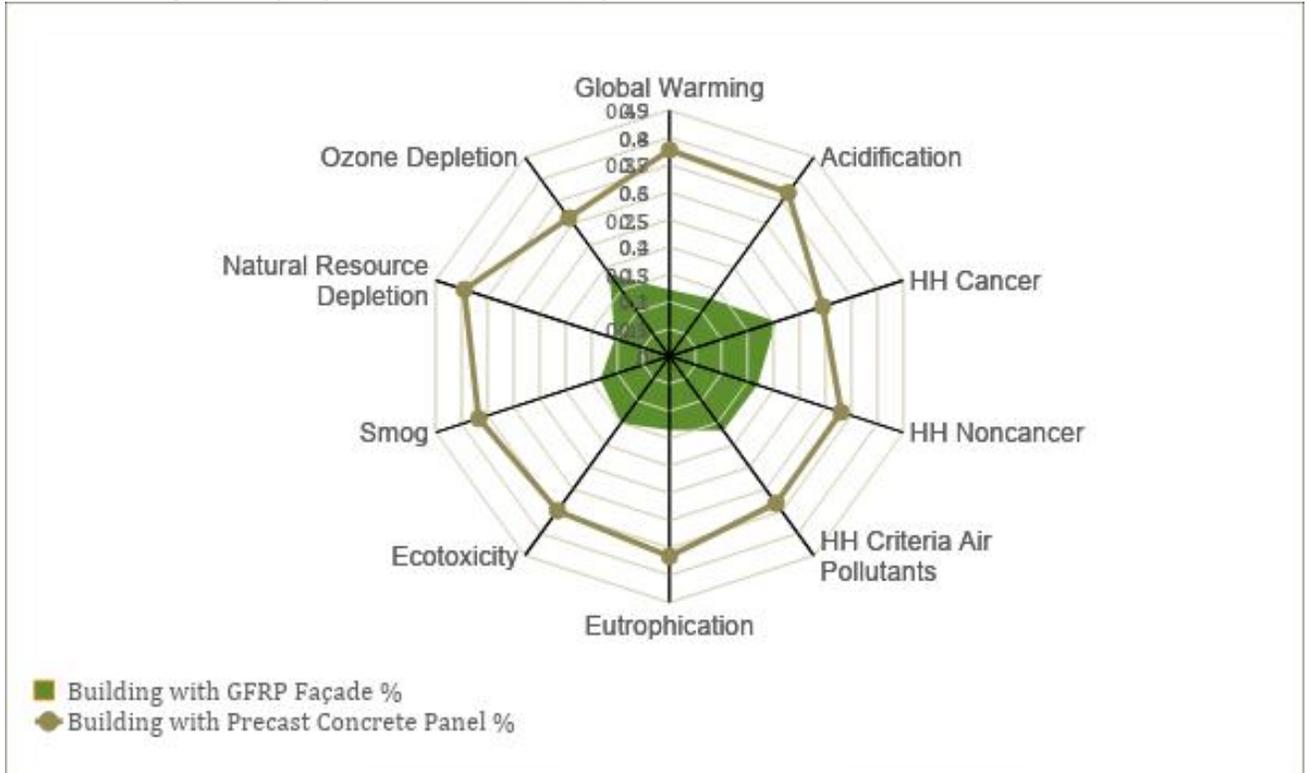
Table 5 shows the differences in emissions by the building with GFRP panels vs. precast concrete panels, as well as the building's land occupation. The functional unit is the building structure. As the results indicate, choosing GFRP panels over precast panels can reduce the emissions of SO_x, NO_x, CO, and ozone by nearly two thirds, CO₂ by around 45%, Pb by 36%, and PM10 by 22%. The reduction of emissions by choosing GFRP panels may also happen during transportation, since the GFRP panels weigh as light as 1.8% of the weight of precast panels needed for the same building structure. Moreover, using GFRP panels decreases the occupations of dump site and construction site by 50%.

Table 5: Life Cycle Impact Assessment of PCC vs. GFRP

		PCC	GFRP
Emissions (tons)	CO ₂	304	209
	NO _x	5.32	1.55
	CO	3.05	2.24
	SO _x	6.51	2.2
	PM ₁₀	0.040	0.031
	Pb	0.60	0.38
	Ozone	1.8E-3	0.664E-3
Land Occupation (ft²)	Dump Site	22604.2	10979.2
	Construction Site	900.9	452.1
Panel Weight (lbs)	Per panel weight	8,402.5	149.6

Figure 1 compares the LCA of a building made of GFRP panels to that of a building constructed of precast concrete panels. As the figure indicates, the precast panels rank higher than their GFRP counterpart in every impact category. The categories with the biggest discrepancies include smog, acidification, global warming, eutrophication and natural resource depletion.

Figure 1. Life Cycle Assessment (LCA) of GFRP Panel vs Precast Concrete Panel



IMPACT SENSITIVITY ANALYSIS

As with any life cycle analysis study, not all data is perfectly uniform and there are certain sensitivities that should be considered to raise the robustness of the study. Major factors that influence the impacts of each material have been examined. Appendix C contains six tornado diagrams showing the ranges of single point score and greenhouse gas impacts for PCC buildings, GFRP buildings and structural steel. For a PCC building, the steel ratio is a major contributor to the extra impacts; varying this from the same amount of steel to double the amount of steel allows for the full range of possibilities to be examined. Concrete thickness and hardware were also examined as they vary with architectural choices on a building project. The potential for higher performance future concrete was also examined by the inclusion of 50% slag; this material change has shown a major reduction in singlepoint and GHG emissions. With the best performance from each of these sensitivities, it can be seen that GRFP performs better environmentally.

For the GFRP building, a major consideration was transportation distance from the American Canyon facility to the project in Southern California. Surprisingly, due to the lightness of the panels, moving the facility to Southern California did not change the single point score and only had a minor impact on GHG emissions. Attachment hardware was also considered as a sensitivity for potential architectural changes.

Sensitivities for structural steel were also considered; their effects on the analysis contribute only to the magnitude of impacts due to the steel being bought from the same source for either instance of the building. The initial analysis considered the steel being bought from a Californian source to avoid new tariff costs on steel imports. This also lessens the transportation impacts. A sensitivity analysis was performed to measure the increase in impacts due to transportation from a Chinese facility. This change has the largest effect of any on the project, as it raises the impacts by three orders of magnitude. The recycling fraction was also changed to see the impact of using new materials vs including repurposing of existing steel.

For the purpose of comparison, the combination of multiple impacts was considered for both GFRP and PCC. When these two possibilities are compared to each other, PCC outperforms GFRP by 300 points or about 3%. The case where all of the sensitivities combine for either material is unlikely, but the comparison shows how much improvement is required in concrete to exceed the performance of GFRP. However, the best case scenario concrete does not outperform the expected case for GFRP. This shows that the conclusions of the analysis will remain the same except for the most extreme case combining the limits of concrete technology and extreme sensitivity effects. A graph comparing the best case and worst case scenarios can also be found in Appendix C.

LIFE CYCLE COSTS

Table 6 shows the life cycle cost breakdown of PCC panels versus GFRP panels for the selected example hotel project. The material cost is considered the same (\$50/sf) for both panels, and it includes the manufacture and transport of raw materials to the plant. (Kreysler) Based on the comparison, the GFRP panels have overall cost advantages over the conventional precast panels.

One of the most significant economic incentives in adopting GFRP panels is the substantial reduction in the use of steel; the lightness of GFRP creates major structural reductions. Since the demand of steel mass for GFRP panels is only 60% of that for the precast panels, the costs related to steel use, such as transportation, erection, and disposal, can all be significantly reduced. Considering that disposal cost is a major concern in the use of precast panels with 100% of the panels going into landfill at the end of their service life, the significant reduction in disposal cost by using GFRP panels can serve as another important reason for choosing GFRP over precast panels. The reduction in disposal costs comes from both lighter trucking mass and the lessening of landfill fees which are mass based.

Due to the lightness of GFRP panels, assembly will likely be easier for the erection crew. Working with lightweight materials will require less lifting equipment and work can be performed in less time. Therefore, adopting the GFRP panels may lead to a more efficient construction process and greater savings in labor cost because it requires half of the total work days required for the construction using the PCC panels. Given the same crew costs for the installation of both precast and GFRP panels, the shortening of the work days results in the reduction of erection cost.

Compared to precast panels, the only drawback in the life cycle cost of GFRP panels lies in transportation cost due to the fact that GFRP panels are produced and manufactured from a farther location. However, such drawback could be compensated by utilizing a local facility for manufacturing panels. It would be possible to create a temporary facility to make panels for a large project if the demand was able to match the cost of setting up another facility.

Table 6: Life Cycle Cost Comparison of PCC and GFRP Panels

	PCC	GFRP	Notes
Total Panels	600	600	8334lf of facade
Work Days	100	50	6 vs 12 panels/day
Materials Cost	\$ 3,990,000	\$ 3,990,000	\$50/sf both panels
Erection Cost	\$ 633,671	\$ 316,835	Crew costs for number of work days
Panel Transportation Cost	\$ 13,711	\$ 16,244	82.4mi trips vs 416.5mi trips
Steel Mass	2,111	1,598	(tons)
Steel Costs	\$ 1,688,800	\$ 1,278,400	\$800 per ton (Alibaba, 2018)
Steel Transportation Costs	\$ 6,997	\$ 4,563	39mi from CA Steel in Fontana, CA
Steel Erection Costs	\$ 1,200,000	\$ 960,000	Scale Estimate
Disposal Mass	5,041,531.25	89,775.00	
Disposal Costs	\$ 293,316	\$ 5,223	NPV-50 years, Steel fully recycled
Total Project	\$ 7,819,498	\$ 6,571,275	

PERFORMANCE DRIVERS AND STRATEGIES FOR IMPROVEMENTS

The life cycle impact assessments and cost breakdowns show that the weight of the selected panel has a significant impact on the project performance in sustainability and economy. At a weight of 149.63 lbs, each GFRP panel weighs 57 times less than each precast panel that weighs 8402.55 lbs. This drastic difference in weight has a major influence on the environmental impacts and costs associated with transportation and disposal, which makes GFRP panels a more sustainable and economic option over their conventional concrete counterpart.

According to the LCA, one key performance driver is the cement content in concrete, which significantly contributes to the high global warming effects and smog associated with precast panels. The cement industry is the third largest source of anthropogenic CO₂ emissions (Earth System Science Data, 2018). The reason for these high CO₂ emissions is that in order for clinker to form, cement has to be heated to extremely high temperatures. Therefore, one strategy for improvement is partially replacing conventional clinker with by-products of other industries that would otherwise be disposed of in landfills, such as fly ash and slag. In fact, a concrete company named Ceratech has begun producing concrete by using 95% fly ash and 5% liquid additives. Sensitivity analysis shows that this change can be a major driver in the reduction of overall concrete life cycle impacts on the project. Another strategy is the use of an admixture called dicalcium silicate which can reduce greenhouse gas emissions by absorbing CO₂ during the concrete curing process.

Another key performance driver is the consumption of diesel fuel by trucks during transport. Replacing diesel with natural gas to power the trucks may result in different emission values of greenhouse gases and pollutants, such as NO_x. Moreover, as natural gas prices have been falling in recent years, using natural gas powered trucks for transport can also cut down the life cycle costs of the panels (Olivier Wyman, 2018).

CONCLUSION

In conclusion, GFRP panels are a more sustainable and economic option than precast panels. As the life cycle cost comparison indicates, installing GFRP panels in favor of precast panels on the selected building results in cost savings of \$1,248,223. In terms of secondary structural effects, if two of the sample buildings are compared - one with 150 pcf precast panels and another with GFRP panels, the former will require 1.32 times more steel than the latter for structural support due to the heavier weight of precast panels. In addition, the impact assessment shows that precast panels are higher than GFRP panels in every impact category and result in higher emissions for every pollutant measured. Therefore, combining the weight reduction structural effects with the lessened material impacts of GFRP creates a much more sustainable building construction option. This analysis concludes that building developers should put considerations into the weight of the materials they are using for their building as there are significant impacts from light-weighting the facade of a building.

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APPENDICES

Appendix A: Structural drawings and Building Rendering for Example hotel building

Figure A.1 Structural model rendering from ETABS

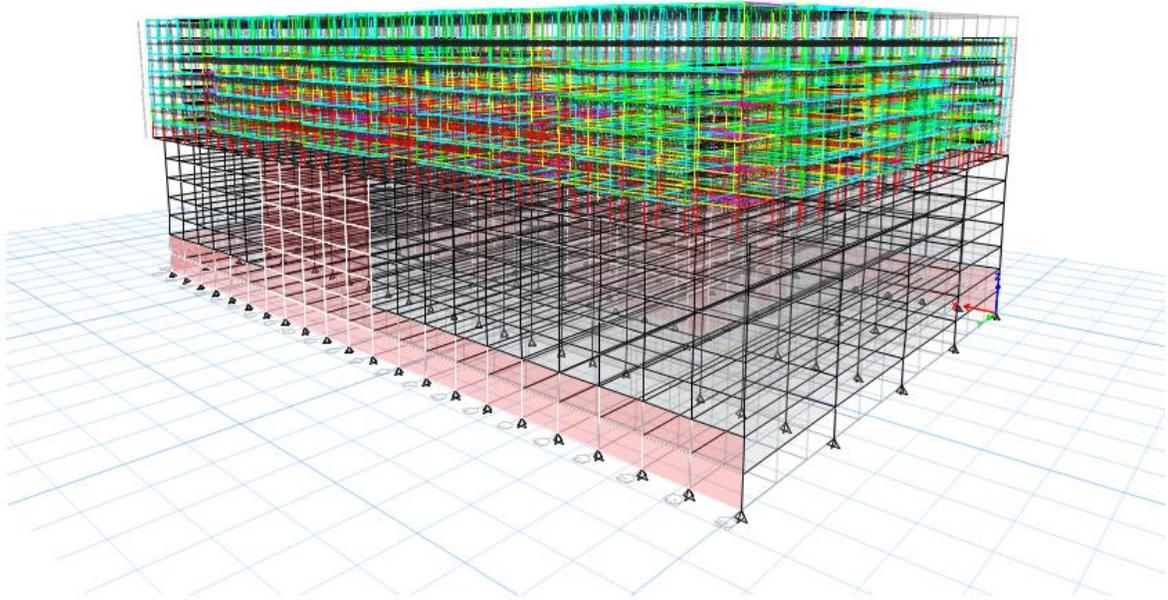
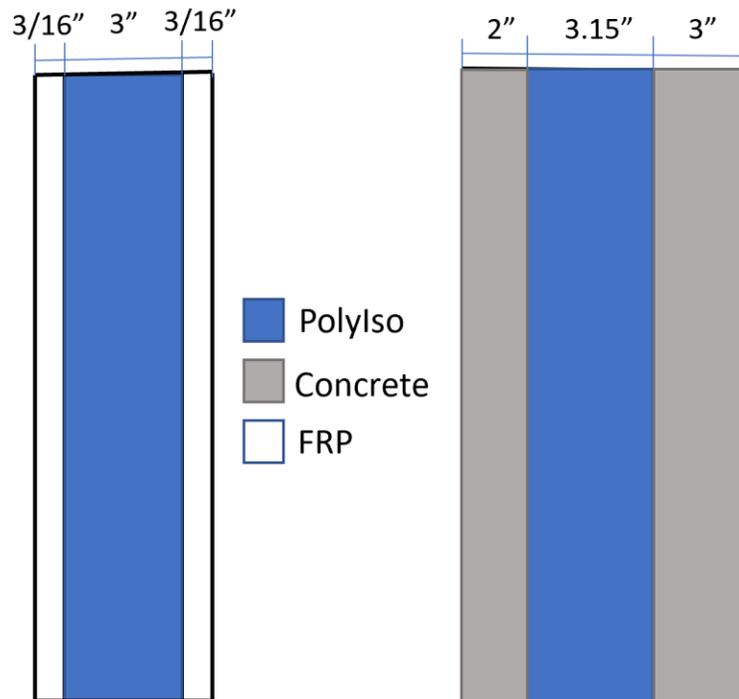


Figure A.2 - Architects rendering of the example building



Figure A.3 Comparison of panel thickness between PC and FRP



Appendix B: Process Flow Diagrams

Figure B.1. Life Cycle Process Diagram of GFRP Panel

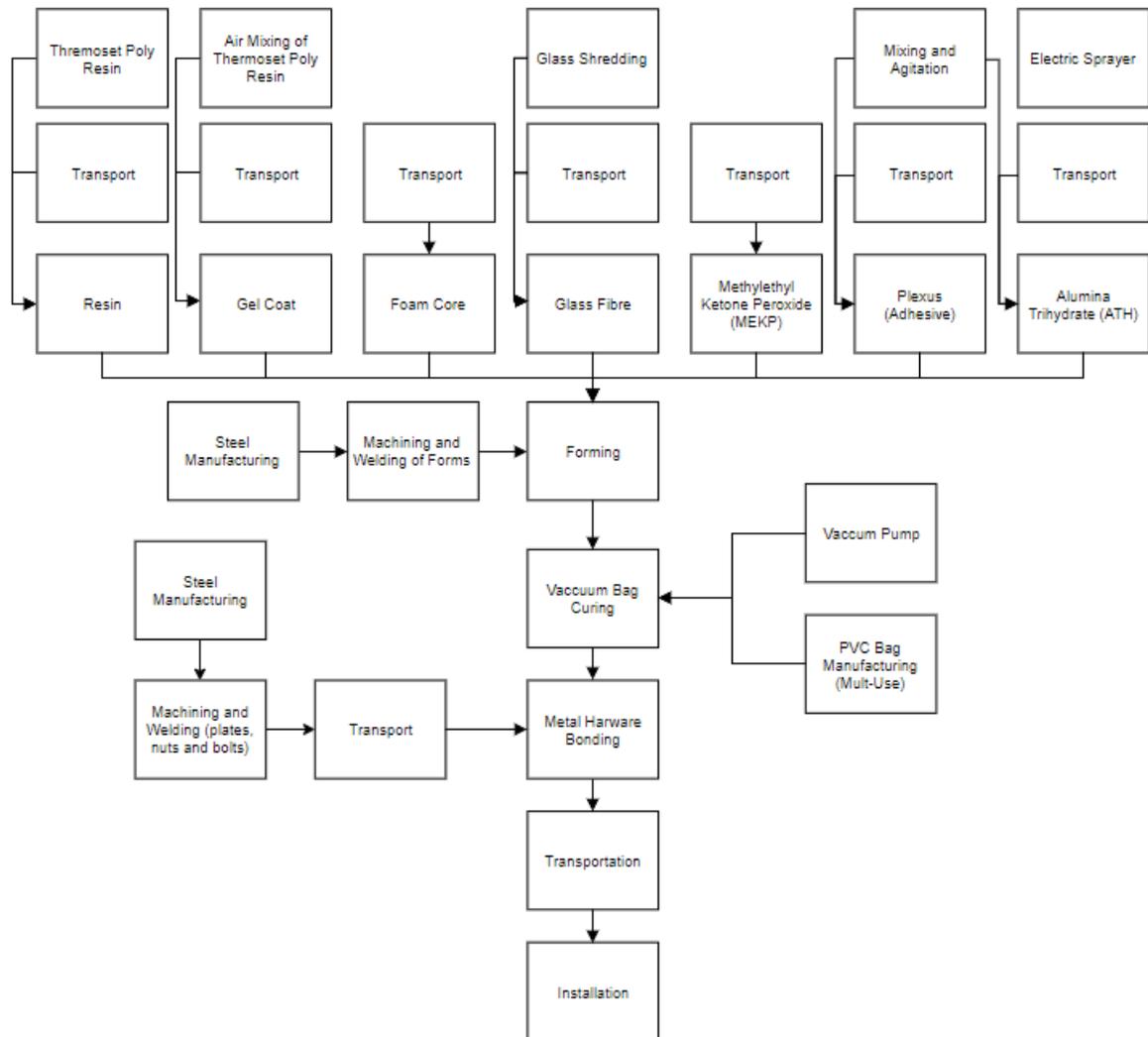


Figure B.2. Life Cycle Process Diagram of Precast Concrete Panel

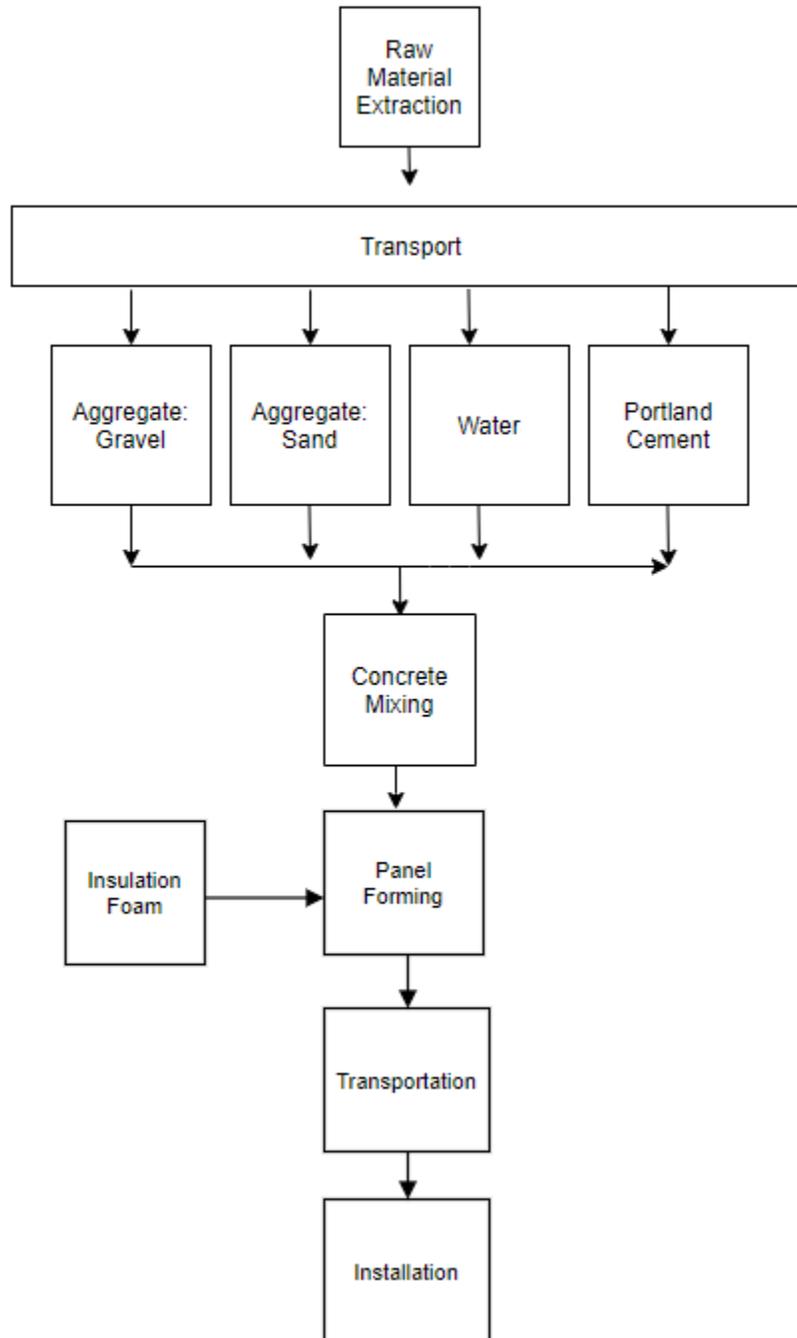
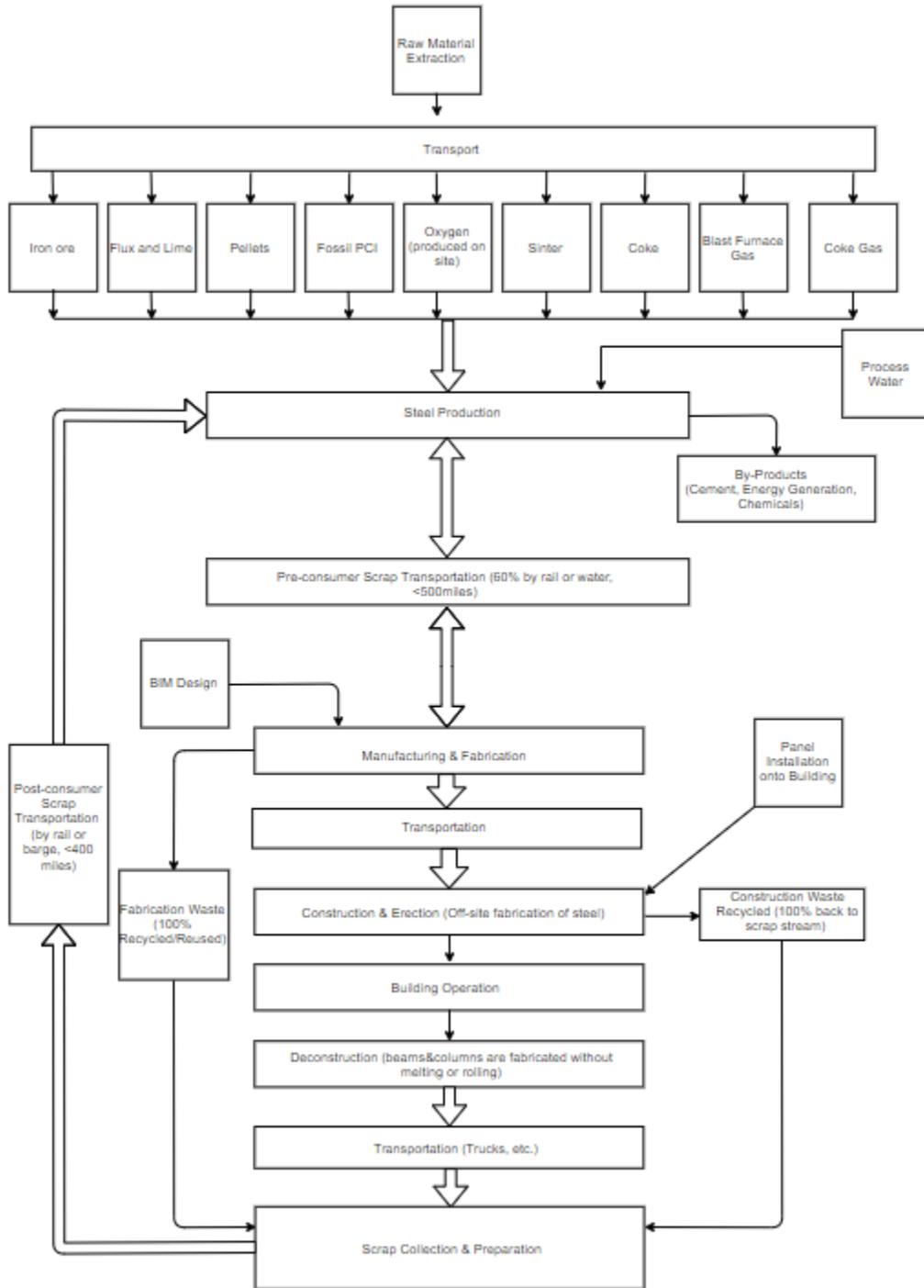
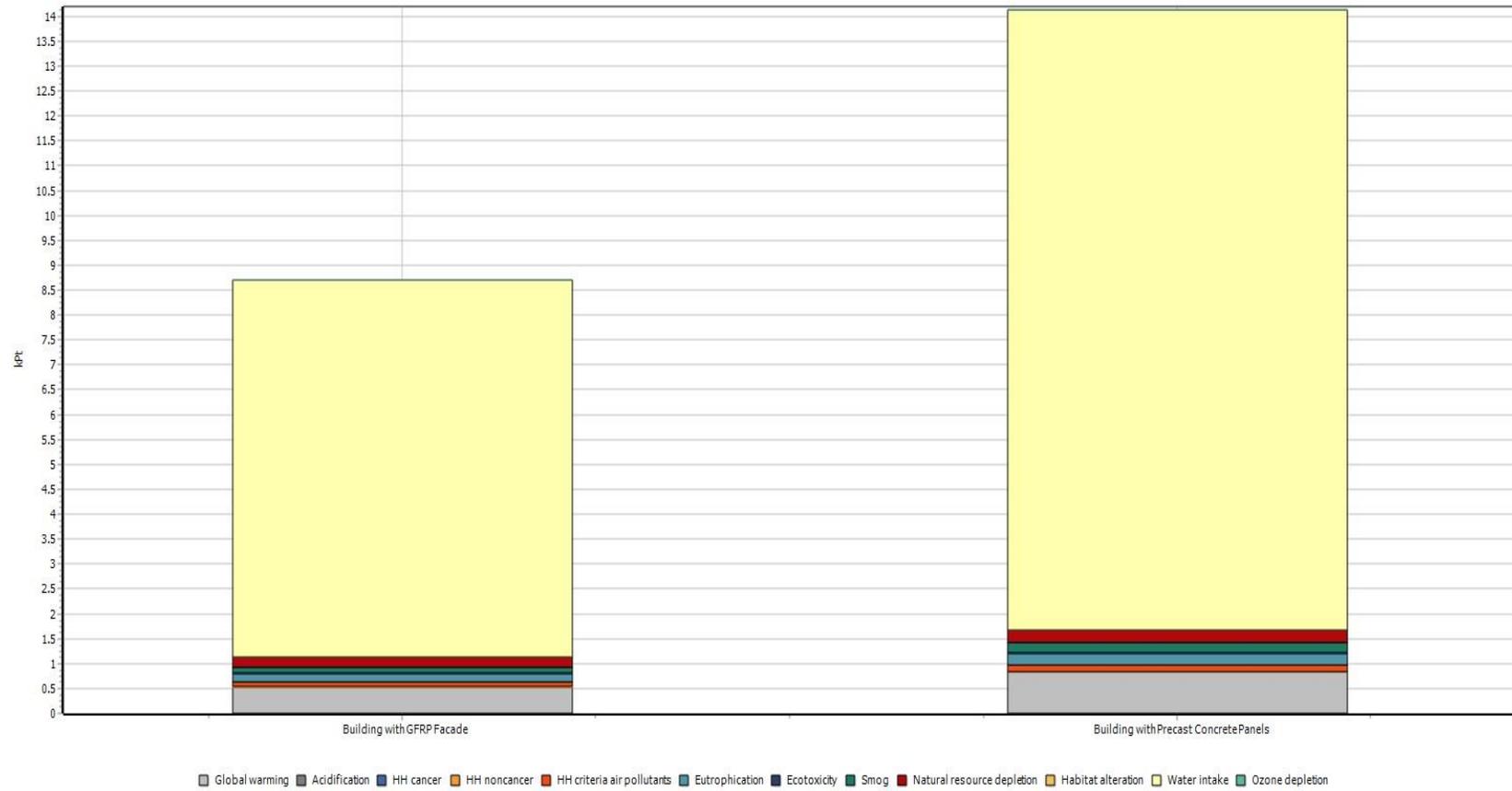


Figure B.3. Life Cycle Process Diagram of Structural Steel



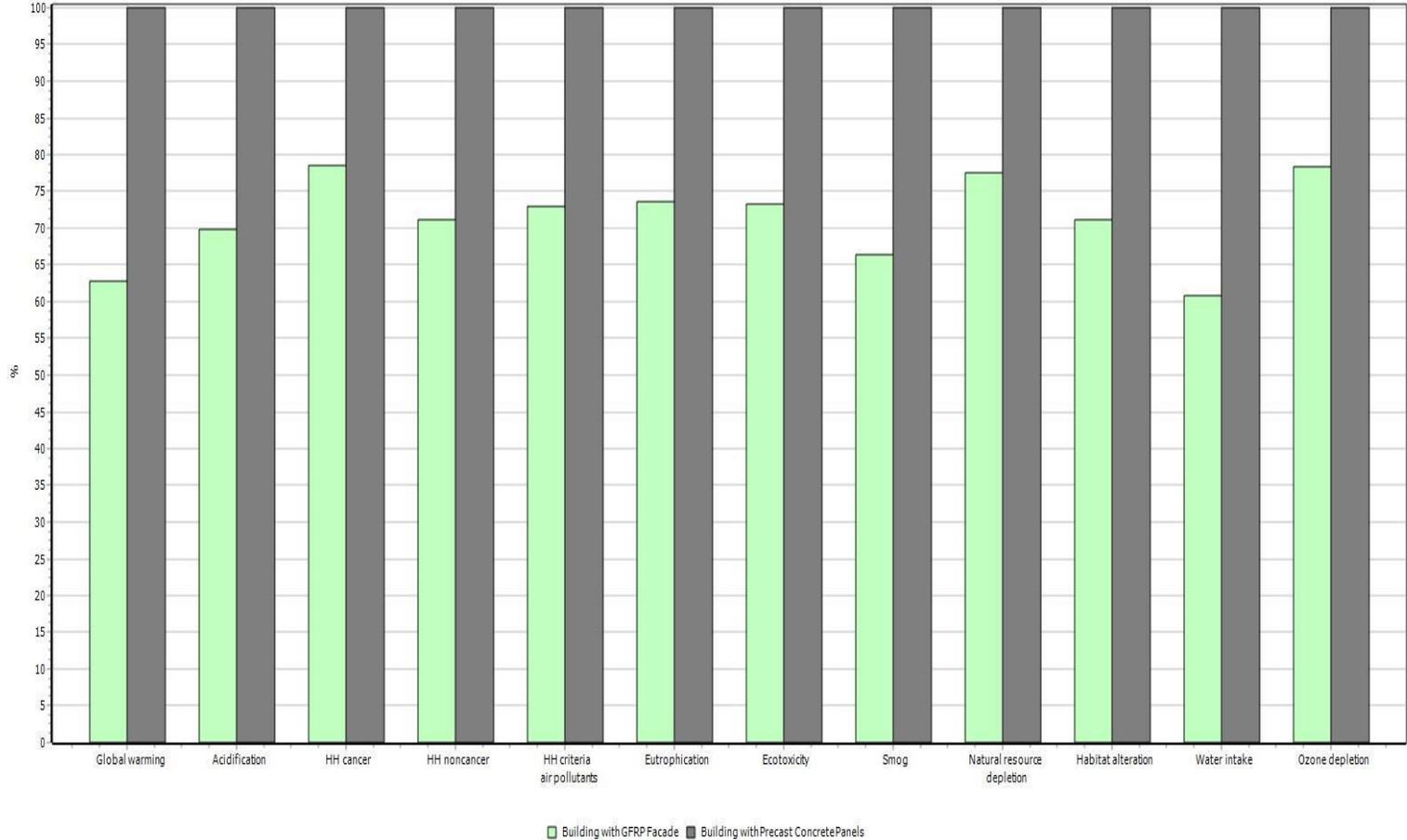
Appendix C: SimaPro Results

Figure C.1. Singlepoint Comparison of Building with GFRP facade to Building with Concrete Facade



Method: BEES+ V4.04 / USA per cap '97-EPA Weighting / Single score
 Comparing 1 p 'Building with GFRP Facade' with 1 p 'Building with Precast Concrete Panels';

Figure C.2. Comparison of Normalized Characterization



Method: BEES+ V4.04 / USA per cap '97-EPA Weighting / Characterization
 Comparing 1 p 'Building with GFRP Facade' with 1 p 'Building with Precast Concrete Panels';

Appendix D: Sensitivity Analysis

Figure D.1 Sensitivity Analysis for PCC Building

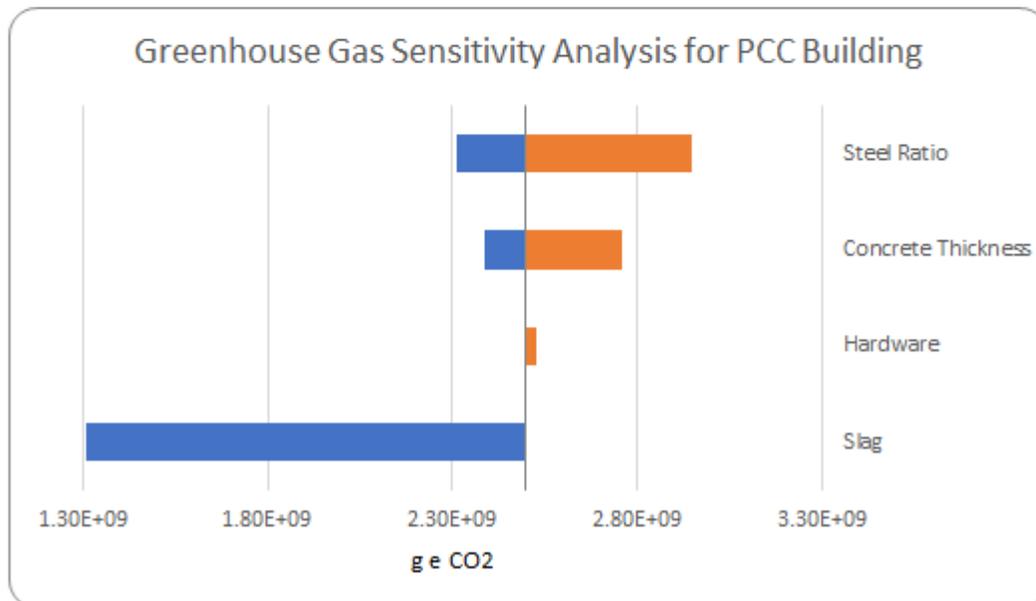
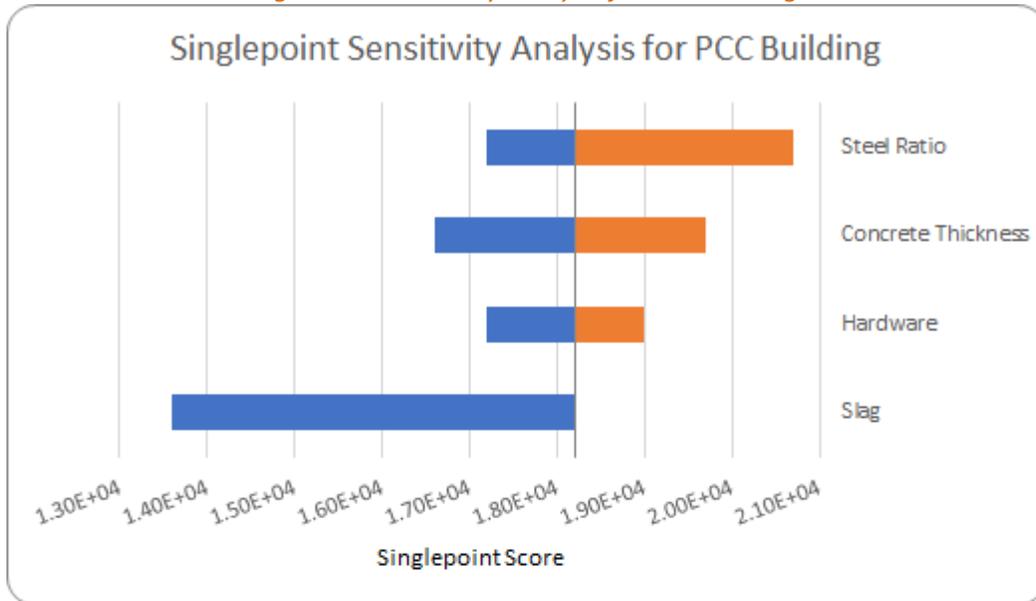


Figure D.2 Sensitivity Analysis for GFRP Building

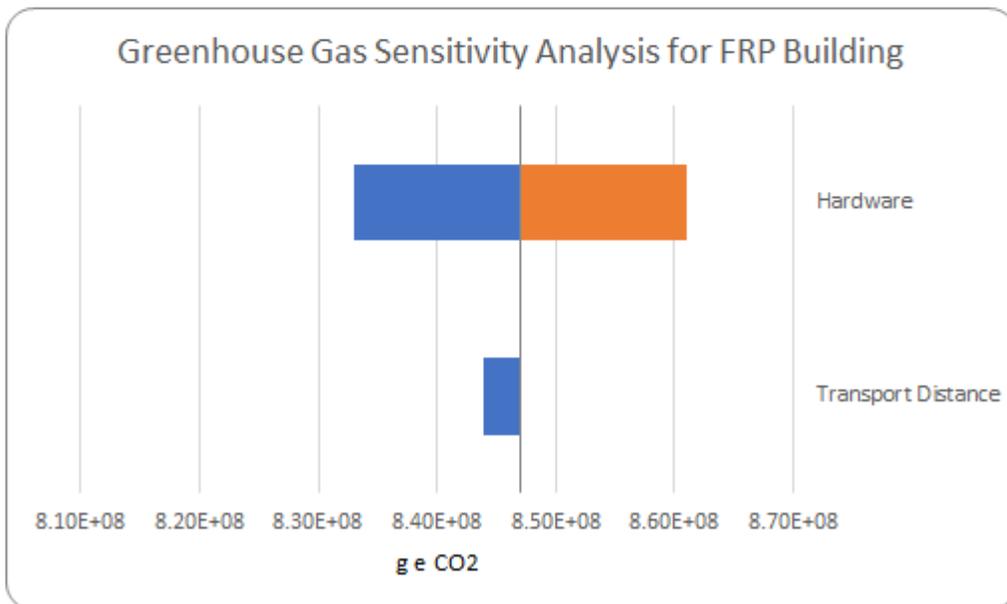
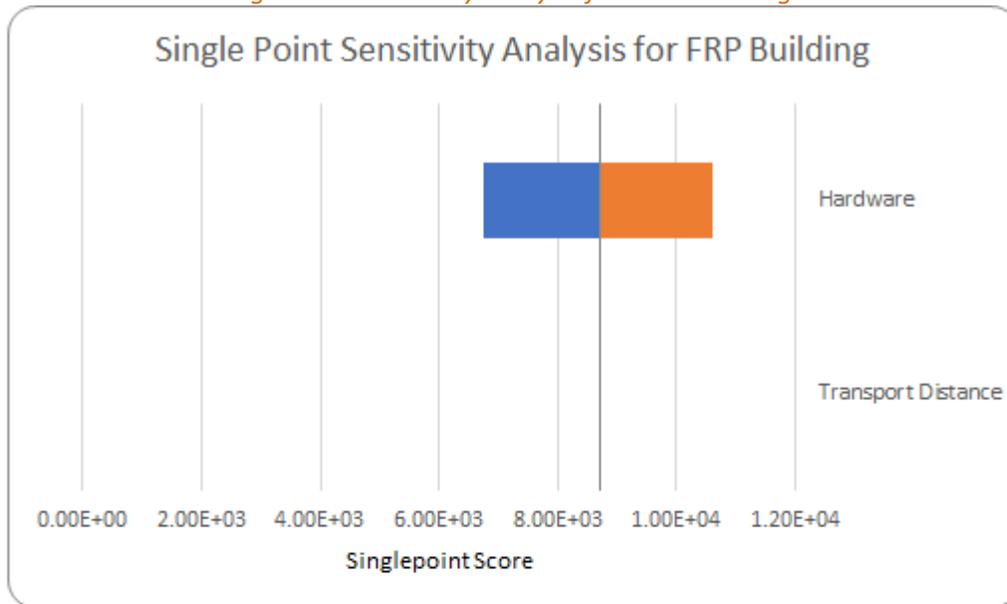


Figure D.3 Sensitivity Analysis of Structural Steel

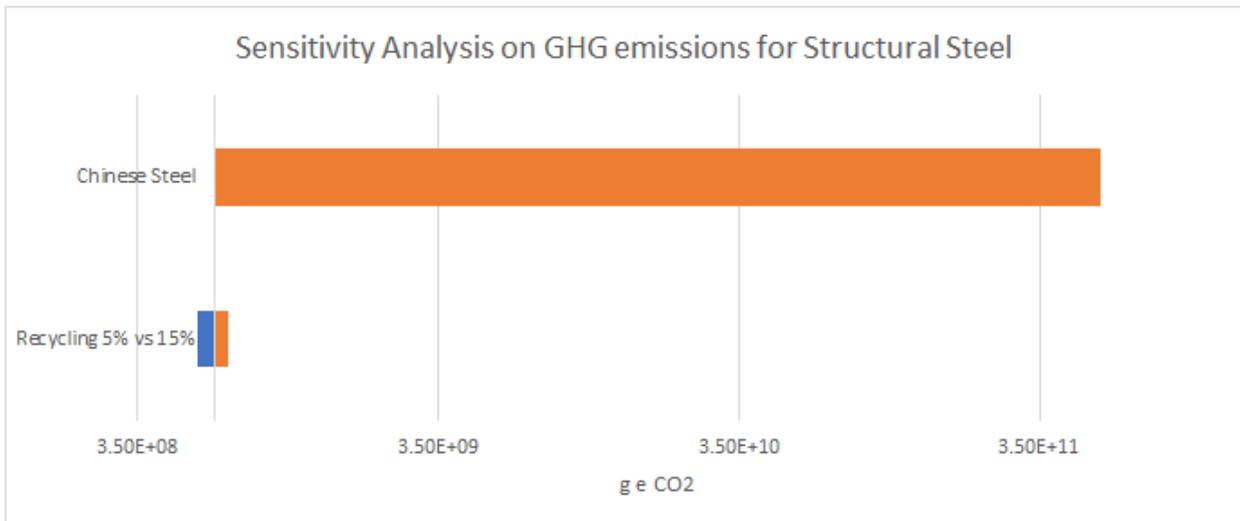
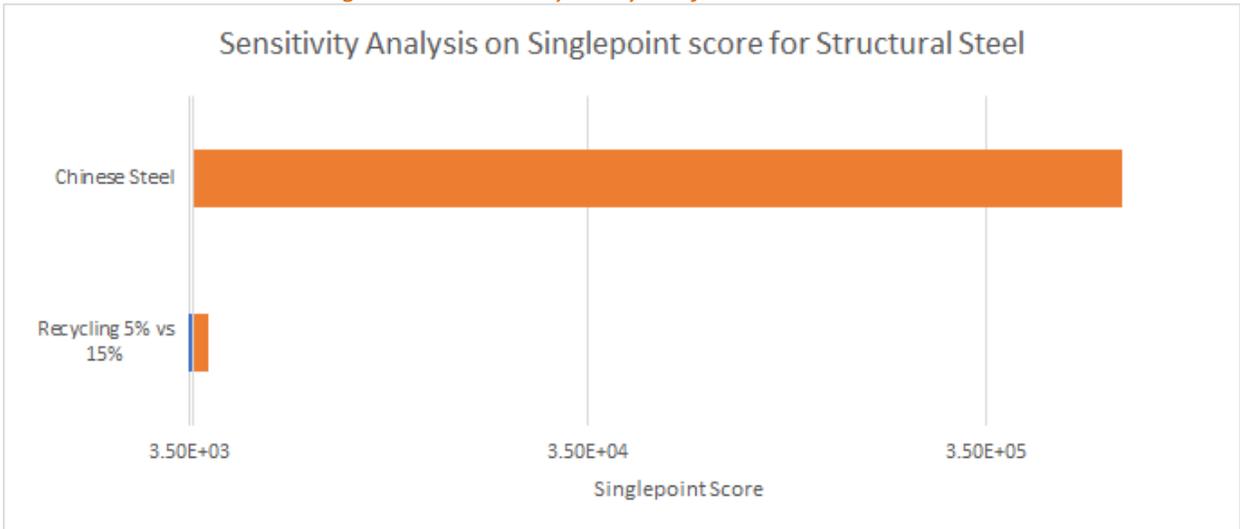


Figure D.4 Cumulative Sensitivity Impact Comparison

