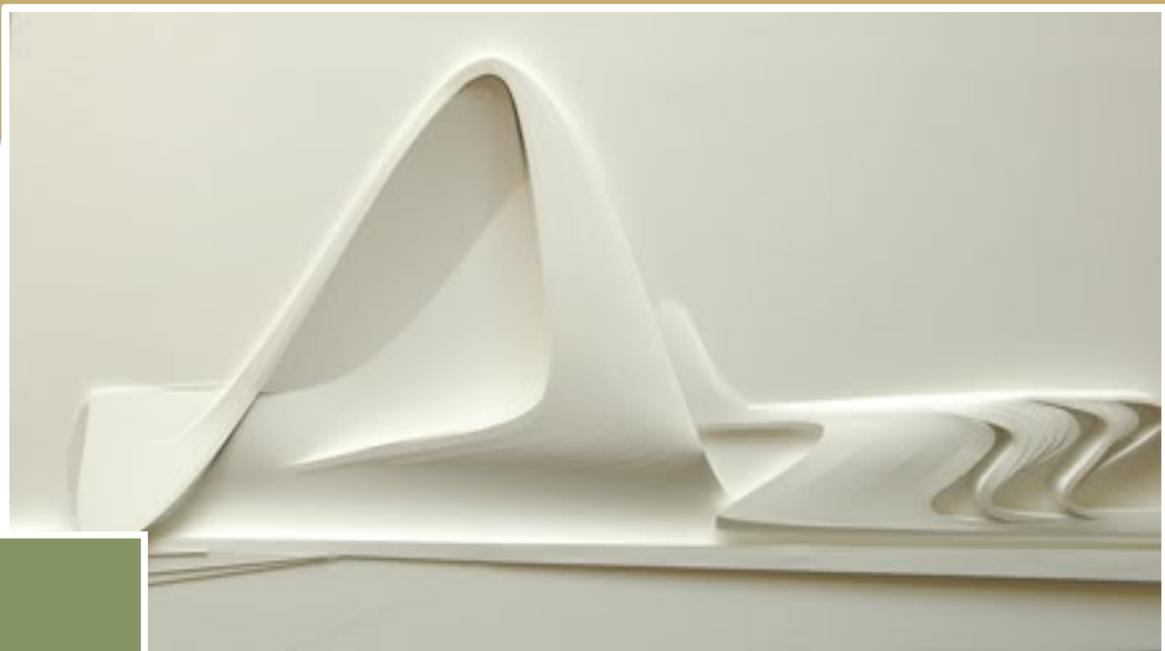
ARCHITECTURAL FAÇADES for the HEYDAR ALIYEV CULTURAL CENTER:

A Life Cycle Assessment



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Abstract

The country of Azerbaijan is in the process of constructing a state of the art cultural center in the nation's capital, Baku. The Heydar Aliyev Cultural Center will be covered in a large façade consisting of 18,000 separate panels. Each panel will be approximately 1 m by 2 m. The façade panels will be made out of either Fiber Reinforced Polymer (FRP) or Glass Fiber Reinforced Concrete (GFRC). To determine which panel has the lowest environmental impact a life cycle assessment (LCA) and an inventory analysis were performed for each panel type.

The LCA for each panel were largely based on the manufacturing and transportation processes. Little was known about the yearly maintenance for each panel, so no panel maintenance was assumed. A replacement rate of 0.5% was chosen for each panel type. The disposal scenario for FRP was 100% land filled and for GFRC a 50% recycling rate. Due to the uncertainty of some of the required information a sensitivity analysis was performed. This analysis included variations in the manufacturing processes of FRP and GFRC, and also changing the transportation scenarios for each panel type.

From the baseline analysis of FRP, the total impact was 1,760 Pt. For the GFRC panels the baseline impact was 6,450 Pt. GFRC has a 266% bigger impact than FRP. GFRC had higher impacts in all major categories except solid waste. The impacts categories that GFRC was higher in include Greenhouse Gases, Ozone Depletion, Acidification, Eutrophication, Heavy Metals, Carcinogens, Summer Smog, Winter Smog, and Energy Resources.

Introduction

The country of Azerbaijan is currently constructing a new cultural center to house a conference hall, museum and cultural library. The building, to be known as the Heydar Aliyev Cultural Center, is of particular importance since Azerbaijan hopes to use it as part of their bid for the 2016 Olympics. The building, as seen in the architectural renderings, has an extensive façade covering its exterior. This façade will be consist of 18,000 panels, approximately 1 m by 2 m. Fiber Reinforced Polymer (FRP) and Glass Fiber Reinforced Concrete (GFRC) have both been proposed as potential materials for the façade. If FRP is chosen, the panels will be manufactured in Istanbul, Turkey and transported to Baku via truck. GRFC panels

Figure 1: Architectural Renderings - Heydar Aliyev Cultural Center

will be manufactured in Stuttgart, Germany and also transported to Baku via truck. To help determine the choice of material, the following report has been compiled to compare the environmental impacts of each panel type using a Life Cycle Assessment (LCA) and Inventory Analysis. This analysis was performed using SimaPro v. 7.0. Data for FRP manufacturing and transportation was obtained through the FRP manufacturer Kreysler & Associates. Data for the GFRC manufacturing process was compiled from industry standards. Material data for both FRP and GFRC were collected on a square-foot basis. The life cycle analysis was conducted using the full building with an estimated lifespan of 50 years. The building has a total area of façade equal to 420,446 sq.ft.

Problem Scope

Process

The following two figures present the process flow diagrams for FRP and GFRC, respectively.

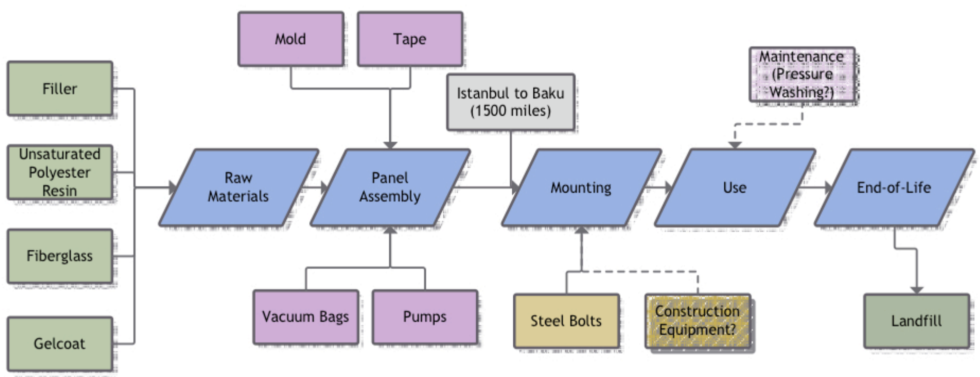

Figure 2: Process Flow Diagram - Fiber Reinforced Polymer

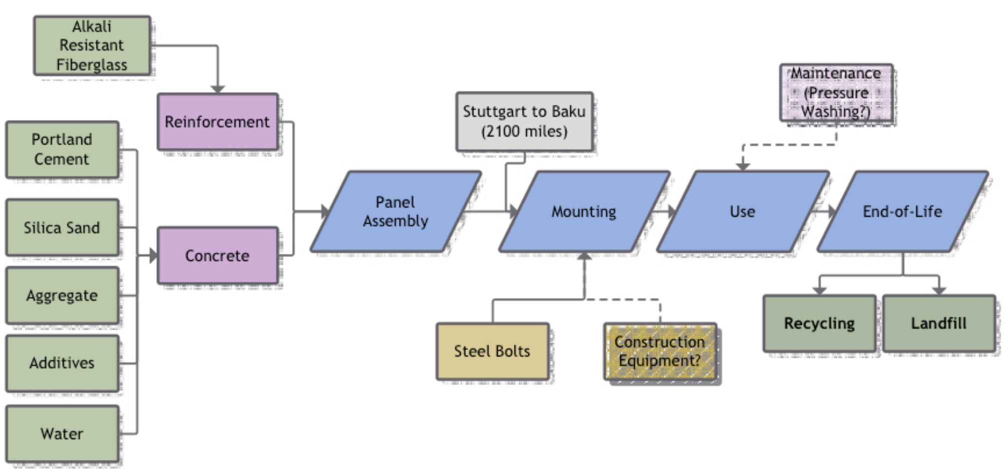

Figure 3: Process Flow Diagram - Glass Fiber Reinforced Concrete

There are a series of steps involved in the FRP manufacturing process:

1. Apply gel-coat as the first layer in a mold.
2. Lay woven fiberglass mat in the mold.
3. Cover the fiberglass with a vacuum bag and seal it with tape.
4. Attach a hose to the vacuum bag and pump out the air.
5. While continuing to pump the air, allow unsaturated polyester resin (UPR) and filler to enter the bag and surround the fiberglass.
6. Continue to run pump until polymer sets, creating a panel.

Figure 4: Panel in vacuuming stage

The GFRC manufacturing process is similar, except cement slurry is used as the composite matrix instead of UPR. The fiberglass is either chopped or woven, as well as alkali resistant to prevent it from reacting negatively with the concrete. The mixture can either be sprayed or poured into the mold.

Assumptions

Both the FRP and GFRC manufacturing processes require use of a similar type of mold. As such, it has been chosen to neglect the mold in the analysis since their environmental effect would be the same for each material and therefore have minimal impact on our comparison.

In Figure 2 and Figure 3 (above), maintenance and construction equipment are shown with hatched coloring and dotted lines. While these two items *are* part of the life cycle of both façade materials, it has been chosen to also neglect these aspects of the process for several reasons. Firstly, it is challenging to predict exactly what maintenance will be required for either façade throughout its life. While some cleaning, such as pressure washing, will be required, quantifying this would be extremely subjective as it is based on the desires of building owners. Secondly, according to Kresyler & Associates, FRP and GFRC are often considered "maintenance-free." While this may too optimistic, it leads one to believe maintenance should be minimal.

Construction was also omitted from the analysis due to quantifying difficulties. Currently the specific type of equipment that will be used for each material is unknown. Most likely, due to the minimal weight of FRP, a crane will not be required. However, the use of a crane is a likely scenario for the GFRC due to its higher weight. Nonetheless, these assumptions are contingent upon many variables, including, but not limited to, construction equipment already on site, available work force, and construction cost restraints. As well, throughout the construction process, some equipment will be used for other tasks in addition to mounting the façade. As such, allocating specific equipment directly to the façade would prove too complex. Initial sensitivity analysis showed that environmental impact was highly contingent on the input value of construction equipment. Taking all of the above factors into account, it was decided that the construction equipment should be left out of the analysis.

The manufacturing location of both materials has not yet been finalized. The proposed location for fabrication of the FRP panels is Istanbul, Turkey. Stuttgart, Germany has been proposed for the GFRC, but this is still uncertain. There is also the possibility that either material could be manufactured more locally in Azerbaijan, particularly in Baku. Based on the likelihood of these scenarios, Istanbul and Stuttgart have been chosen for the manufacturing locations for the base case analysis. In addition analysis has been conducted considering only minimal transportation, to determine the level of effect of choosing local manufacturing. Details of each of these analyses can be found in results below.

Inventory Analysis

FRP Panels

According to the manufacturer, the composition (per square foot) of the FRP panel is: 0.25 lb. gelcoat (NPG gelcoat), 1.0 lb polyester resin (Hetron 814A), 0.67 lb. alumina trihydrate filler, and 0.72 lb glass (alternating layers of 24 oz woven roving and 1.5 oz CSM). Additional materials required in the manufacturing process are vacuum bag plastic (product # RBG 2601-MCF), which may be reused for approximately 50 parts, and rubber tape (product # GS 43 MR 1/8"x1/2"x25'), which is not reused. The manufacturing process also requires 2 hours of vacuum pumping with an 816.5 W pump. A mold is also required in the process, but since the same type of mold is use for both the FRP and GFRC, it was not included in the model.

GFRC Panels

Data on the specific design or manufacturing process of the GFRC panels was not available, and therefore industry standards were used to generate an approximate design. Initially, the model included a GFRC panel thickness of 3” (a verbal recommendation from an industry professional). However, after performing the sensitivity analysis (described in Section 4), it was clear a refined thickness should be determined. This updated thickness was calculated such that the GFRC and FRP panels would have equal flexural strength based on industry-tabulated values. The average value of maximum stress for FRP is 20,000 psi, and for GFRC is from 1,300 to 2,000 psi. Flexural strength is defined as: $\sigma = 3FL / 2bd^2$, where F is the force applied in a three-point loading test, L is the length of the specimen, b is the width, and d is the thickness. Using an average of 1650 psi for the flexural strength of GFRC, a thickness of approximately 1.5" was calculated to match the flexural strength of 0.433" (11mm) thick FRP. The estimate for the glass content of the GFRC, suggested by Bill Kreysler, was 8% by volume, and is within the normal range of industry standards.

Mounting Hardware

A conservative initial estimate of the mounting bolts for the FRP panels was set at (6) 3/4”ϕ x 8” for both the FRP and GFRC. However, after the sensitivity analysis (detailed in Section 4), bolt sizing for FRP was sharpened by Kreysler & Associates to (6) 1/2"ϕ x 6" steel bolts per panel. A similar mounting configuration of (6) 1.2"ϕ x 6"steel bolts per panel was assumed for the GFRC. The 1.2" diameter bolt was determined by scaling the cross sectional area of the bolt to the weight of the GFRC panel in order to account for the additional load.

Shipping

Trucking mileage was estimated by measuring the direct distance from the location of manufacture to Baku, Azerbaijan in Google Earth, and multiplying by a factor of 1.5 to approximate a road path length. Shipping from Istanbul was estimated to be 1500 mi, while shipping from Stuttgart was estimated to be 2100 mi.

Replacement Rate

Since no hard data on the replacement rate of the paneling was available, we assumed a 0.5% per year baseline in order to model this factor's impact. This is an average value over the full life span (approximately 50 years); replacement is not expected every year.

Recycling Rates

We assumed a 0% recycling rate for the FRP panels, as there is currently no method known to recycle FRP. A base recycling rate of concrete was assumed to be 50% in order to model that factor's sensitivity. While some reports say that almost all concrete can be recycled, it is usually is ground and reused for aggregate. Because the GFRC requires a cement slurry mixture, no aggregate is used, thus potentially changing the effective recycling rate.

SimaPro

A number of the aforementioned raw materials and processes were not found directly in the SimaPro database, and therefore surrogates were used, as described below.

Alumina Trihydrate (ATH), a typical filler material for pigments and plastics, was not found in SimaPro. According to the Huber Materials data sheet (as provided by Kreysler & Associates), ATH is 64.9% aluminum oxide (Al_2O_3), and 34.6% is loss on ignition, making ATH 98.6% aluminum oxide after ignition. Therefore, it was determined that aluminum oxide, a material available in the SimaPro database, is a satisfactory surrogate.

The GFRC concrete matrix was modeled using the basic concrete available in the SimaPro database. Although this is likely to be accurate, it exists as a surrogate for an unknown mix design used by the manufacturer.

The alkali resistant glass (AR glass) used in the GFRC was modeled using the fiberglass material available in the SimaPro database. Although the addition of zirconia could make the process more energy and resource intensive, it was determined that the high uncertainty in the percentage of glass used, and the low sensitivity of that variable do not warrant a more accurate surrogate.

Analysis

Sensitivity Analysis – Initial

As discussed in the above inventory analysis, many assumptions and estimations were made in order to obtain SimaPro inputs. As such, sensitivity analyses were conducted to determine which variables had the most acute effect. This analysis was performed by running the model with all estimated variables scaled by ± 25%. The results of these analyses were then compiled to create tornado diagrams for each environmental impact category.

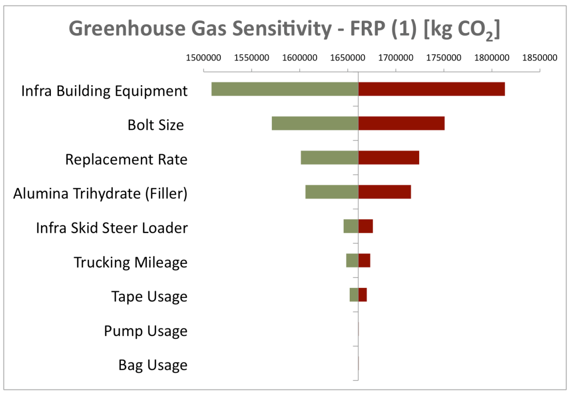

Figure 5: Example FRP Sensitivity Diagram

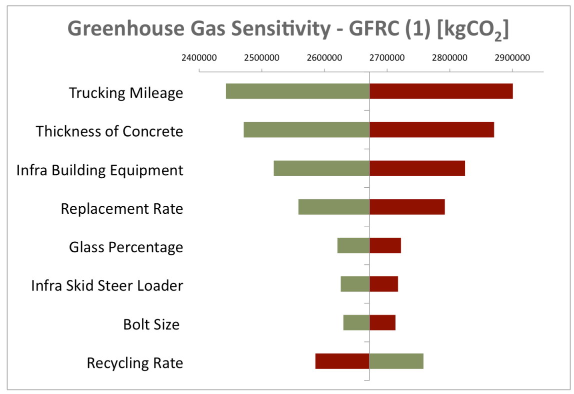

Figure 6: Example GFRC Sensitivity Diagram

Figure 5 and Figure 6 above are examples from the initial analysis showing sensitivity to emissions of CO2 equivalents. (A complete set of impact category tornado diagrams are given in Appendix C). These diagrams demonstrate the high sensitivity of the construction equipment. The decision to omit this equipment from the final analysis was based on these results as well as the high level of uncertainty in the original construction equipment value estimate.

Figure 5 and Figure 6 also show the high level of sensitivity of the bolts. At this stage of analysis, the bolts were estimated to be the same size for both panel types. Since the bolts were found to have substantial effects on the final results, it

was determined that the estimated bolt contribution should be refined to include the fact that the GFRC panels will require larger bolts to account for their heavier weight.

Thickness of the concrete panel at this stage had been estimated at 3” based on industry recommendations. However, the sensitivity analysis showed that GFRC panel thickness is highly sensitive and therefore it was decided that the panel thickness would be refined based on the comparison of the flexural strength of the FRP panels (see inventory analysis, Section 3.0)

Sensitivity Analysis - Refined

Following the initial round of sensitivity analysis, as well as the omission of the construction equipment and the modification of the bolt and GRFC panel thickness data, the sensitivity analysis was re-conducted, this time also incorporating more variables. Figure 7 and Figure 8 below show the results of the sensitivity analysis for SimaPro's single point value for FRP and GFRC respectively. From these figures, it can be seen that the Panel Size as well as the Trucking Mileage are highly sensitive for both materials.

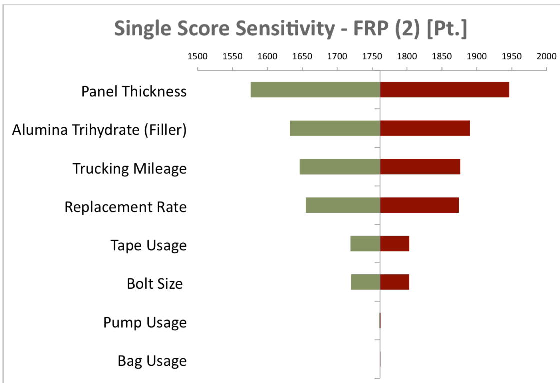

Figure 7: Example Refined FRP Sensitivity Graph

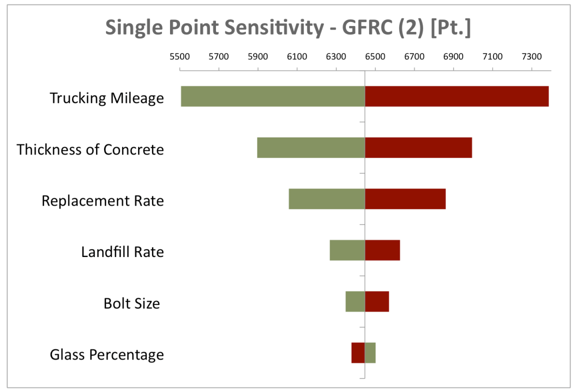

Figure 8: Example Refined GFRC Sensitivity Graph

It was interesting to note that the Alumina Trihydrate filler is very sensitive (more so than any other raw material for FRP). Although the filler is known to a high degree of certainty, this does show that Alumina Trihydrate is a potential target for further optimization.

Glass percentage is shown reversed in the above figure for GFRC. In order to keep the panel thickness constant as well as the increase the glass fiber content, the amount of concrete is decreased. This reverse relationship shows that concrete is more impactful.

Life Cycle Analysis Results

Initial – Baseline LCA Results

As mentioned previously, the baseline case was chosen with manufacturing of the FRP panels occurring in Istanbul and manufacturing of the GFRC in Stuttgart. Using SimaPro's single score impact evaluation, FRP (single point = 1761) was found to have less environmental impact than GFRC (single point = 6447). The following figure shows the weighting of each impact category for both FRP and GFRC using SimaPro's single point weighting system. It can be seen from this figure that GFRC has higher impact than FRP

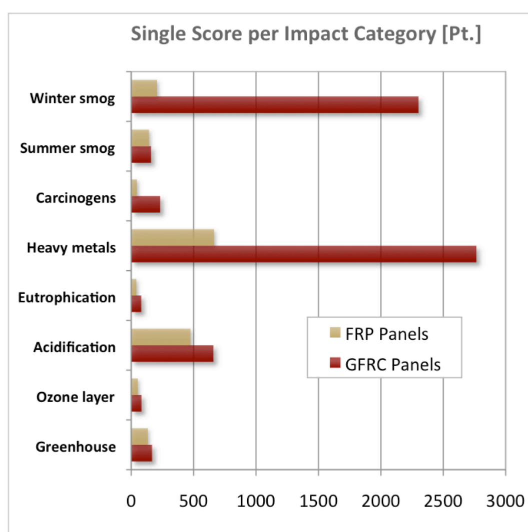

Figure 9: Baseline Individual Impact Categories

in every category except solid waste. A particularly significant discrepancy is in the heavy metals and winter smog categories. It can be reasoned that these high values are the result of the high level of transportation from Stuttgart required for the GFRC and the production process of Portland cement, respectively. The highest impact category for the FRP is heavy metals, which is likely attributable to the transportation requirement from Istanbul, but it is still significantly lower than the impact from heavy metals for the GFRC.

LCA Results – Transportation Comparison

The sensitivity analysis determined that the results are highly dependent on the amount of transportation used for both the FRP and GFRC. Since the location of fabrication for both materials is uncertain, it was decided that the best way to compare both materials was to conduct additional analyses for minimal transportation. The value of transportation for these cases was set to 200 miles, approximately 10% of the distance required for original transportation of the GFRC from Stuttgart. Transportation was not set to zero since it would be highly likely that even if the materials were fabricated locally they would still need to be transported a minimal distance.

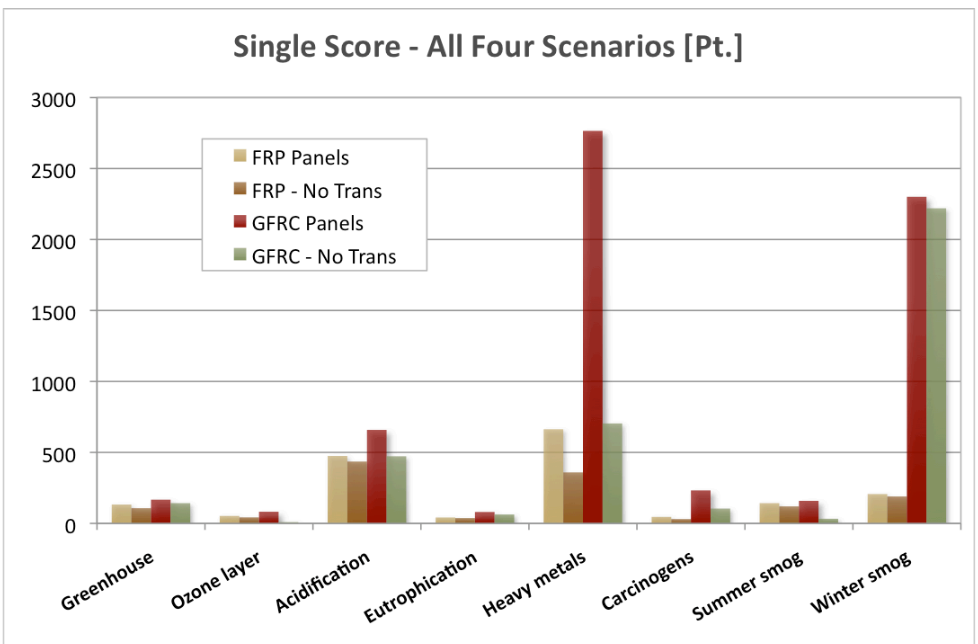

Figure 10: Transportation Analysis Summary

Figure 10 shows that regardless of transportation, GFRC still has a large impact on winter smog. Reduction of transportation for the GFRC however, decreases its heavy metals impact to a value approximately equal to the FRP fabricated in Istanbul. On the other hand, the FRP without transportation has the lowest impact from heavy metals. For most impact categories the level of difference between each of the four scenarios is minimal, making a final conclusion between the materials difficult.

LCA Results – Primary Drivers and Mitigation Strategies

Reviewing each stage of the LCA, weight appears to be a common thread for performance of both materials. Weight depends on the amount of material used, and subsequently has an effect on the steel mounting brackets, construction equipment requirements, transportation emissions, as well as the building's structural system. FRP's reduced weight helps to make it more competitive than GFRC.

Heavy metals were a high impact category for both GFRC and FRP. These emissions are primarily caused by use of diesel trucks for the panel's transportation. The steel mounting brackets are also partly contributable. One method of reducing environmental impact from heavy metals is to produce the chosen material locally. This is more likely a possible scenario for the GFRC since its manufacturing location is less certain. However, choosing to produce GFRC locally creates another important decision that needs to be made. Winter Smog, another high impact category for GFRC, is a local pollutant. If the manufacturing of GFRC is completed in Azerbaijan, the pollutant would have most effect on the local area. As such, Azerbaijan will need to decide whether or not that they are willing to accept the higher local environmental impact in return for a lower global environmental impact.

A second strategy for reducing heavy metal impact would be to use an alternative mode of transportation. For instance, both trains and barges are known to be more efficient than diesel trucks. However, this strategy depends on the availability of equipment and specific location of the project.

A third strategy for reducing heavy metals is to simply use FRP instead of GFRC. Producing GRFC in Stuttgart had an impact for heavy metals approximately five and half times greater than the FRP produced in Istanbul. Both transportation and bolt requirements are less for the FRP than the GFRC, so FRP is the best option for this category.

A large portion of GFRC's environmental impact was found to be the result of winter smog. There are several potential alternatives that could be used to reduce this impact. Firstly, use of fly ash in the concrete mix would reduce the overall Portland cement content, which is the primary cause of the high winter smog of concrete. Furthermore, currently in Italy, a specialized concrete that claims to be 'smog eating' is under development. This concrete, known as TX Active, and claims to convert NOx and SOx into harmless nitrates and sulfates, respectively, when the concrete is exposed to smog. This concrete is currently experimental, but the option of its use still exists. Finally, and most obvious, choosing the FRP panels can easily minimize winter smog because no Portland cement is required.

Life Cycle Costs

The cost for the FRP panels is $26.16 per square foot and the total cost is $11.0 million. These cost figures were directly from the manufacturer, Kreysler & Associates. The total transportation cost for FRP from Turkey is $260,000. The end of life disposal cost of FRP will be $1000, this will make the total life cycle cost $11.2 million. GFRC panels will cost $30.9 per square foot making the total manufacturing cost $13.0 million. Due to the weight of GFRC and the longer distance of shipping from Stuttgart, the shipping cost will be $4.2 million. The end of life disposal will cost $1,400, this makes the total life cycle cost of GFRC $17.3 million. Due to the international nature of the project there is more uncertainty in the cost of GFRC since we were not in contact with the manufacturer. Therefore less emphasis was placed on the life cycle cost analysis for the two panels. Overall, it is safe to say that the heavier GFRC will make the construction, transportation, and tipping more expensive than FRP.

Conclusions

In conclusion, initially assumptions found FRP to be more environmentally friendly with a single score value from SimaPro 72% less than the GFRC. Minimizing transportation requirements for both materials showed that the FRP still remained higher than the GFRC in all impact categories except for summer smog. However, the GFRC did become significantly more competitive when the transportation was minimized. Taking this information into consideration, along with the fact that FRP is highly durable and has a higher strength per unit weight, we recommend the use of FRP for the Heydar Aliyev Cultural Center. However, if GFRC is chosen, we highly recommend that it be produced locally such that the environmental impact due to transportation are minimized.

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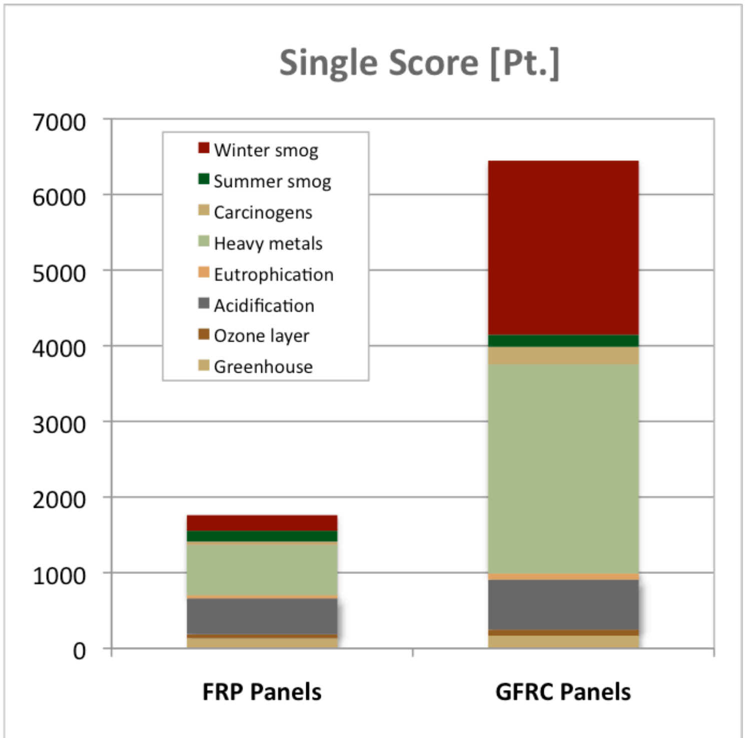
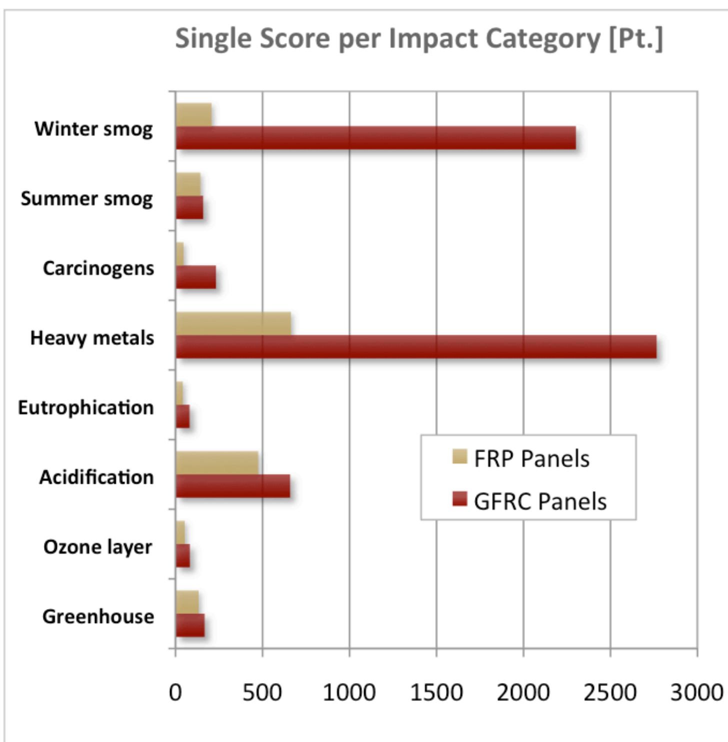
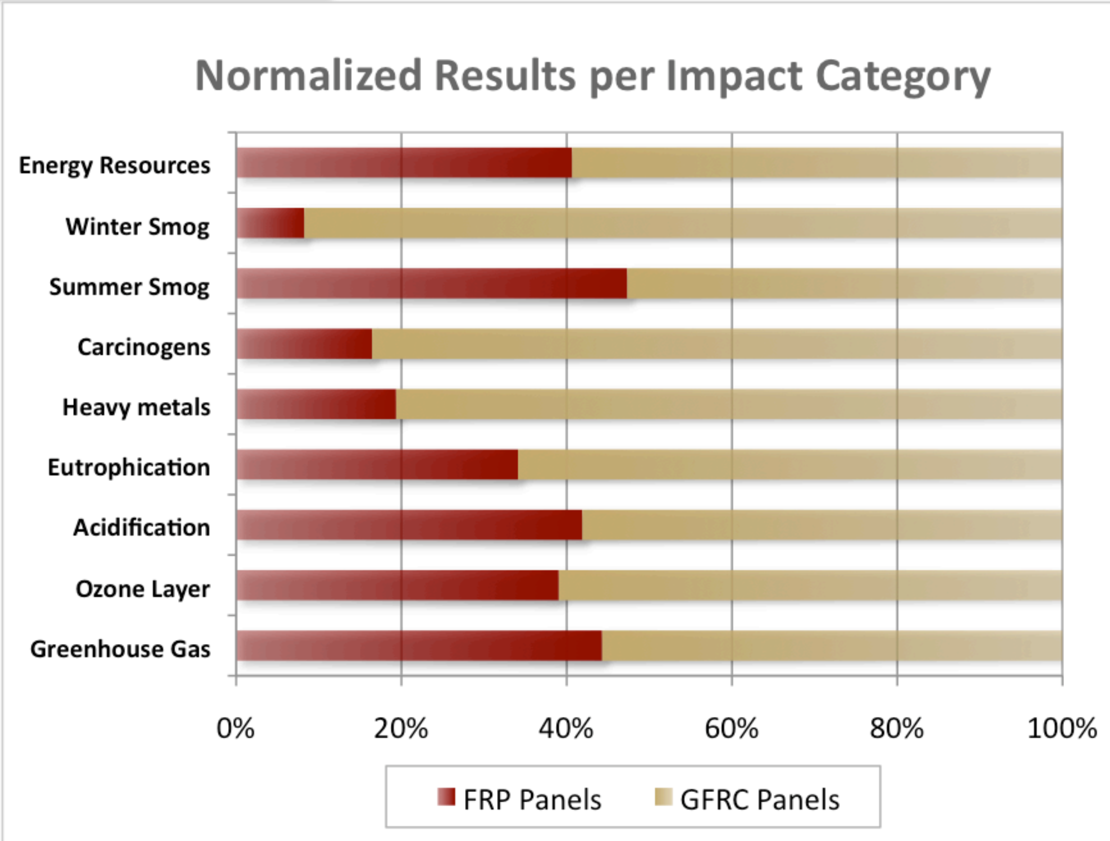
Appendix A: SimaPro Results – Baseline

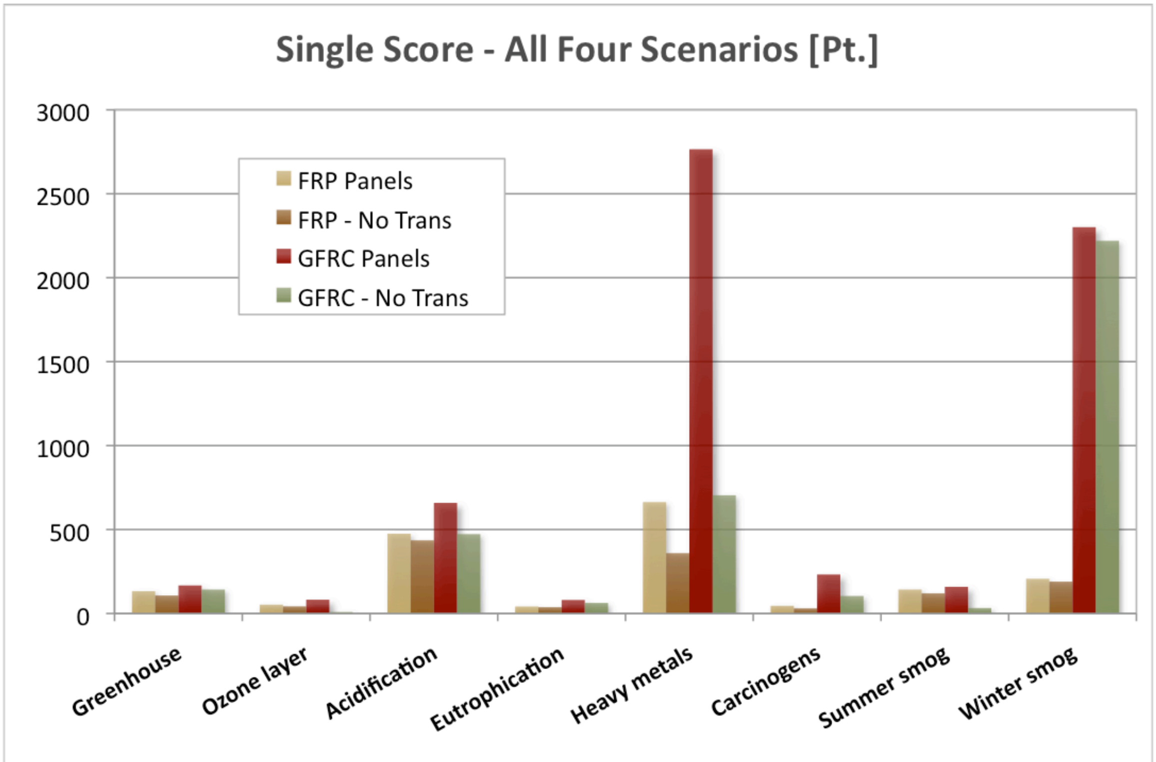


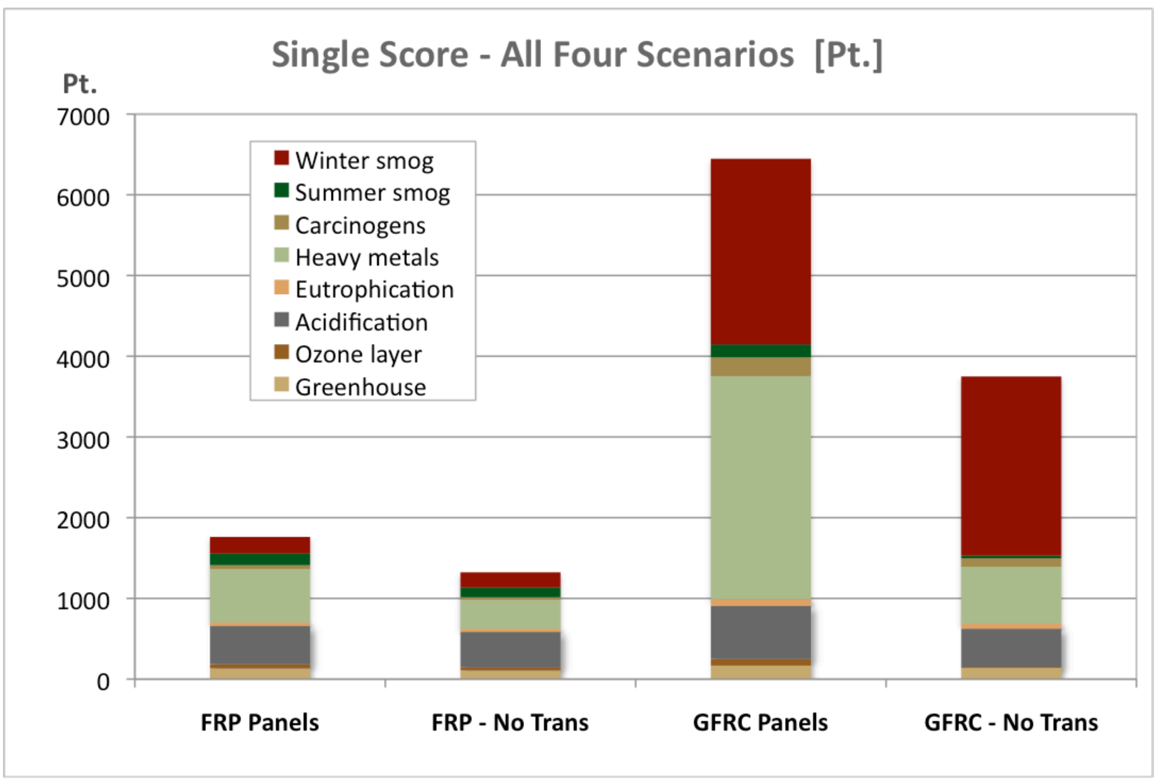




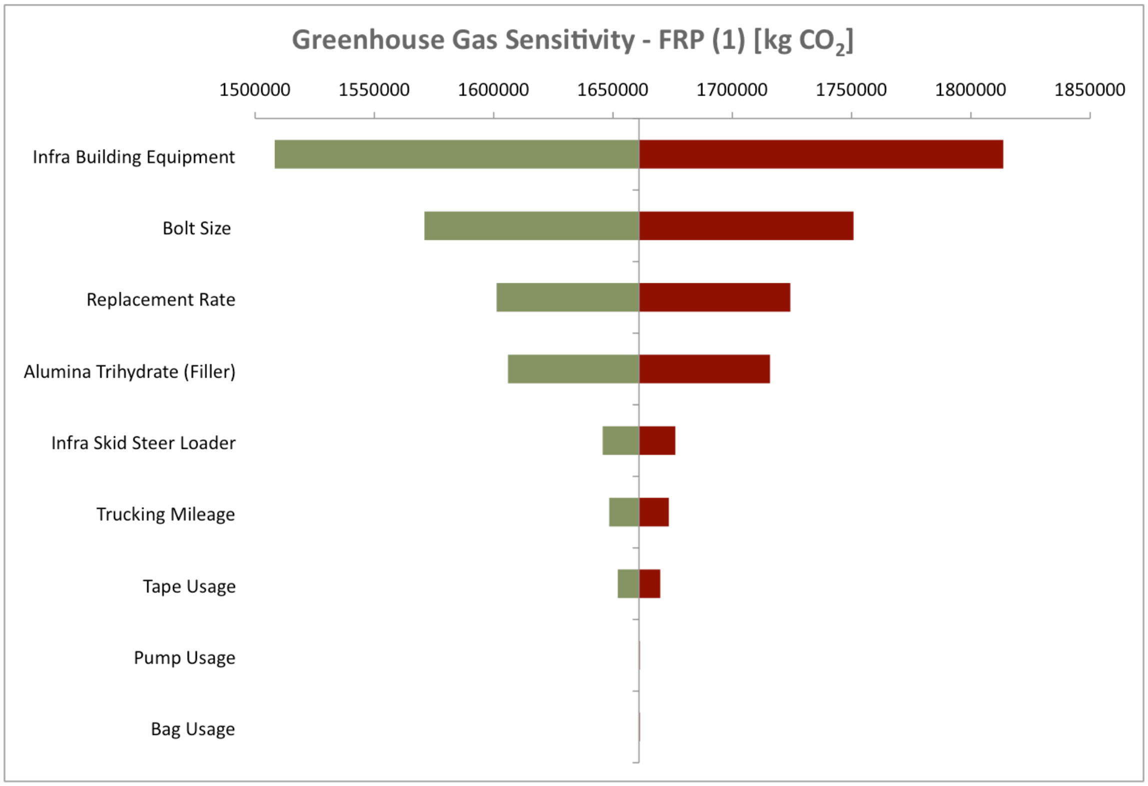
Normalized Results per Impact Category
Energy Resources
Winter Smog
Summer Smog
Carcinogens
Heavy metals
Eutrophication
Acidification
Ozone Layer
Greenhouse Gas
0%
20%
40%
60%
80%
100%
FRP Panels
GFRC Panels

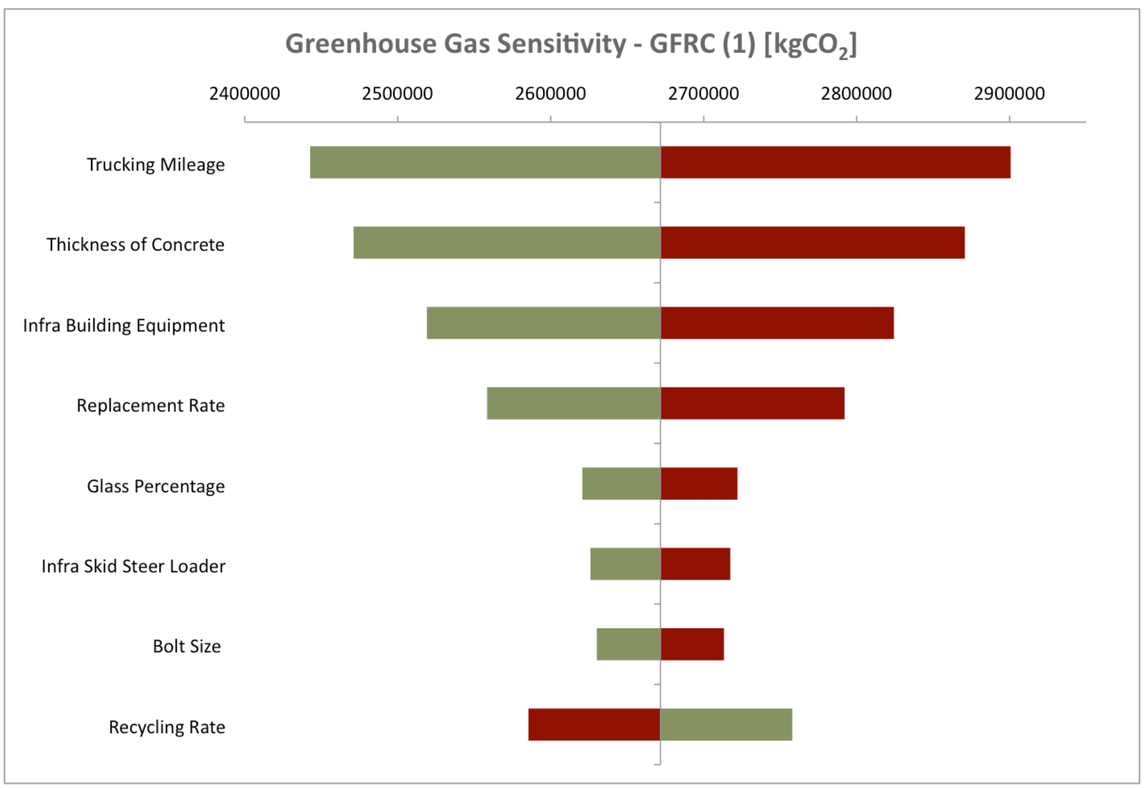
Appendix B: SimaPro Results – Transportation Analysis

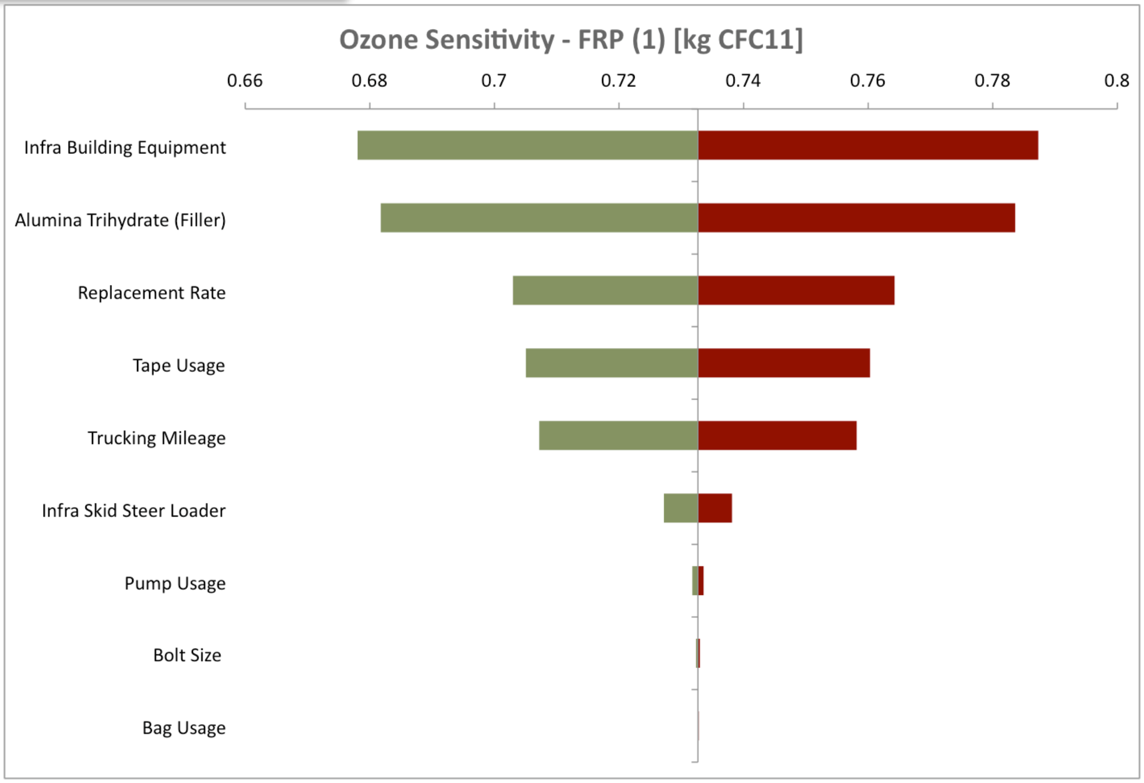


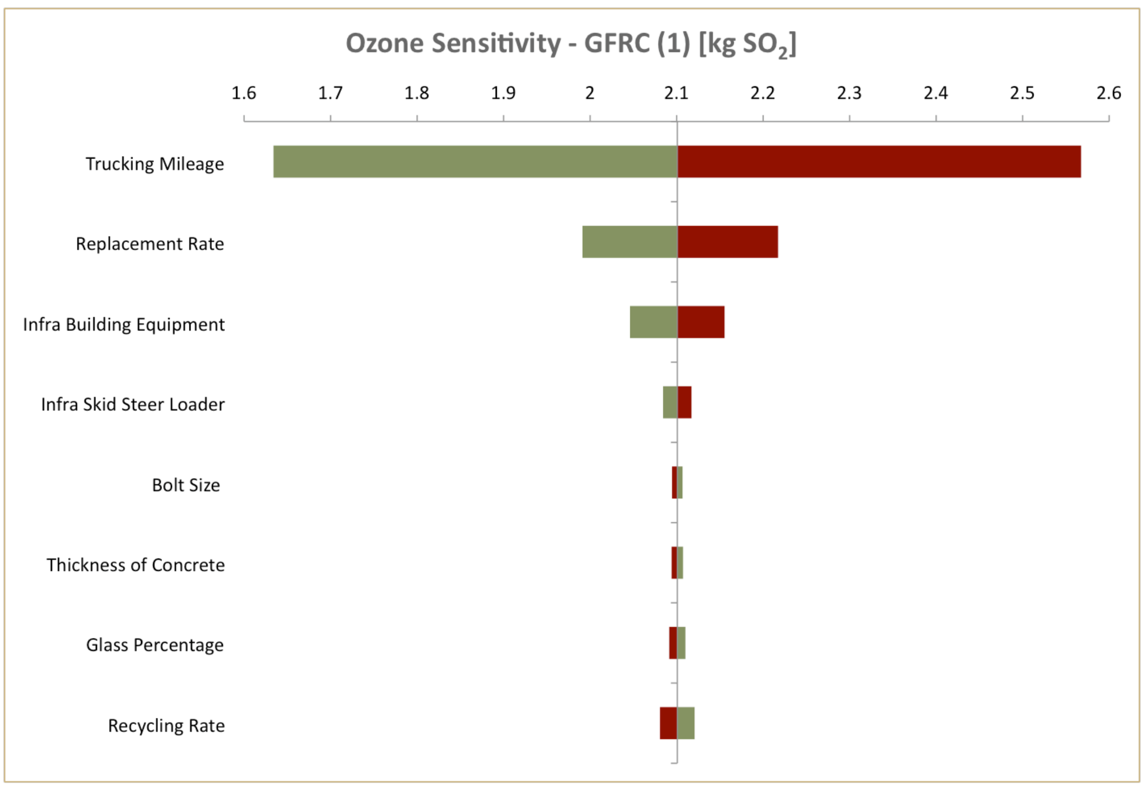


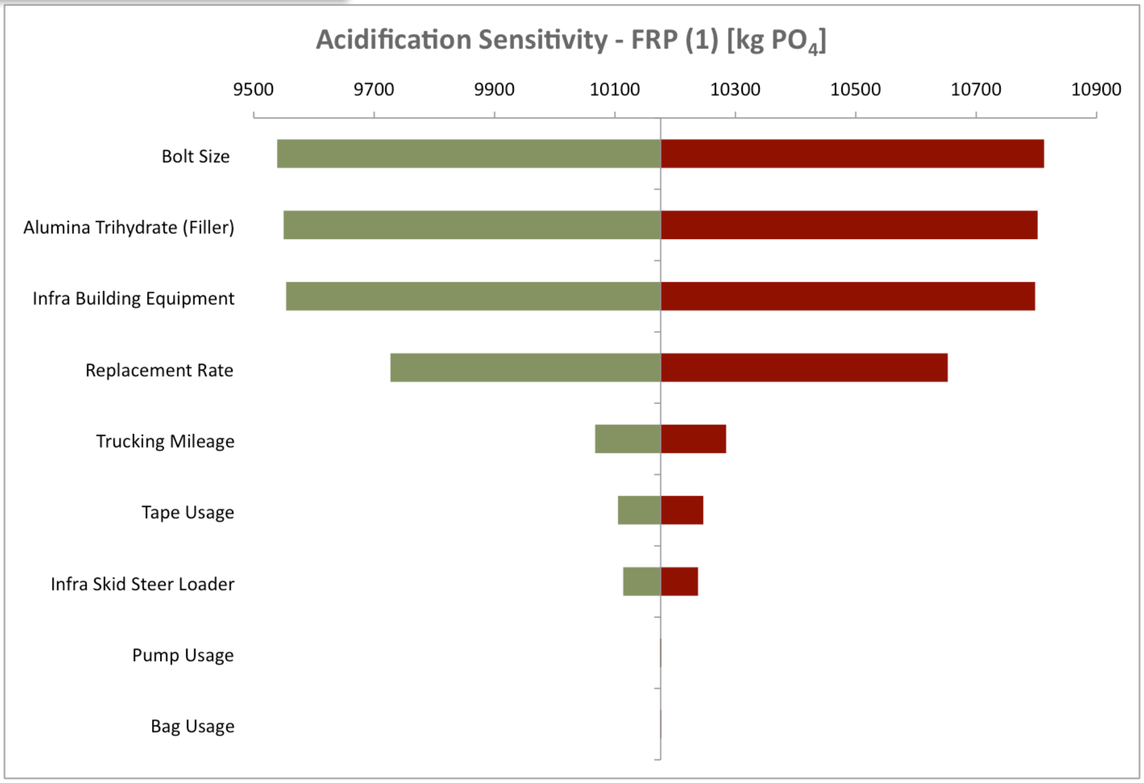
Appendix C: Initial Sensitivity Analysis Results



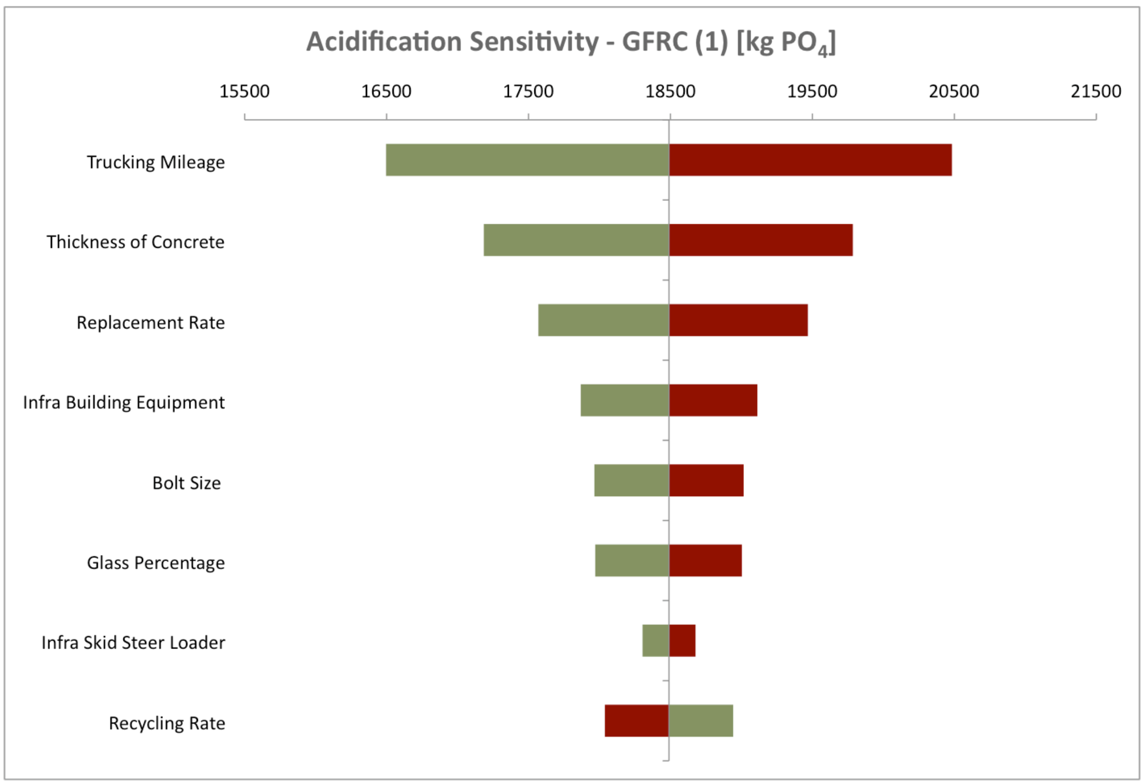



Ozone Sensitivity - FRP (1) [kg CFC11]
0.66
0.68
0.7
0.72
0.74
0.76
0.78
0.8
Infra Building Equipment
Alumina Trihydrate (Filler)
Replacement Rate
Tape Usage
Trucking Mileage
Infra Skid Steer Loader
Pump Usage
Bolt Size
Bag Usage

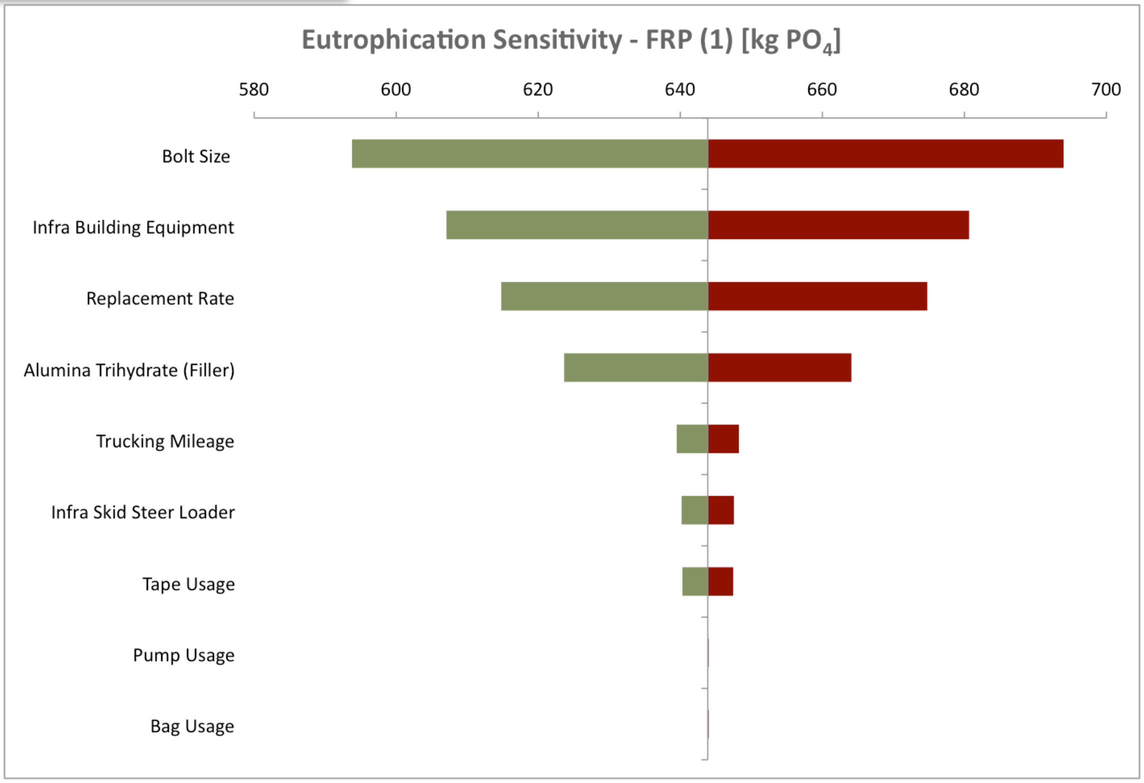

Ozone Sensitivity - GFRC (1) [kg SO_2]
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
2.5
2.6
Trucking Mileage
Replacement Rate
Infra Building Equipment
Infra Skid Steer Loader
Bolt Size
Thickness of Concrete
Glass Percentage
Recycling Rate

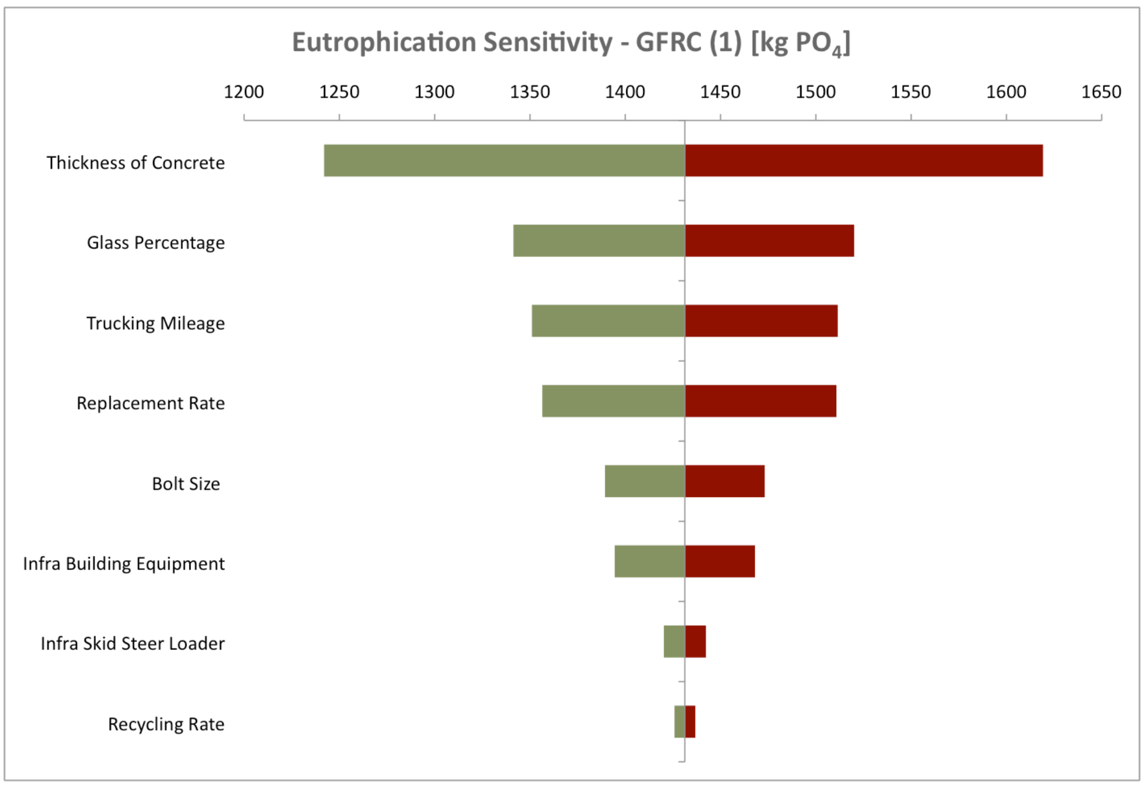


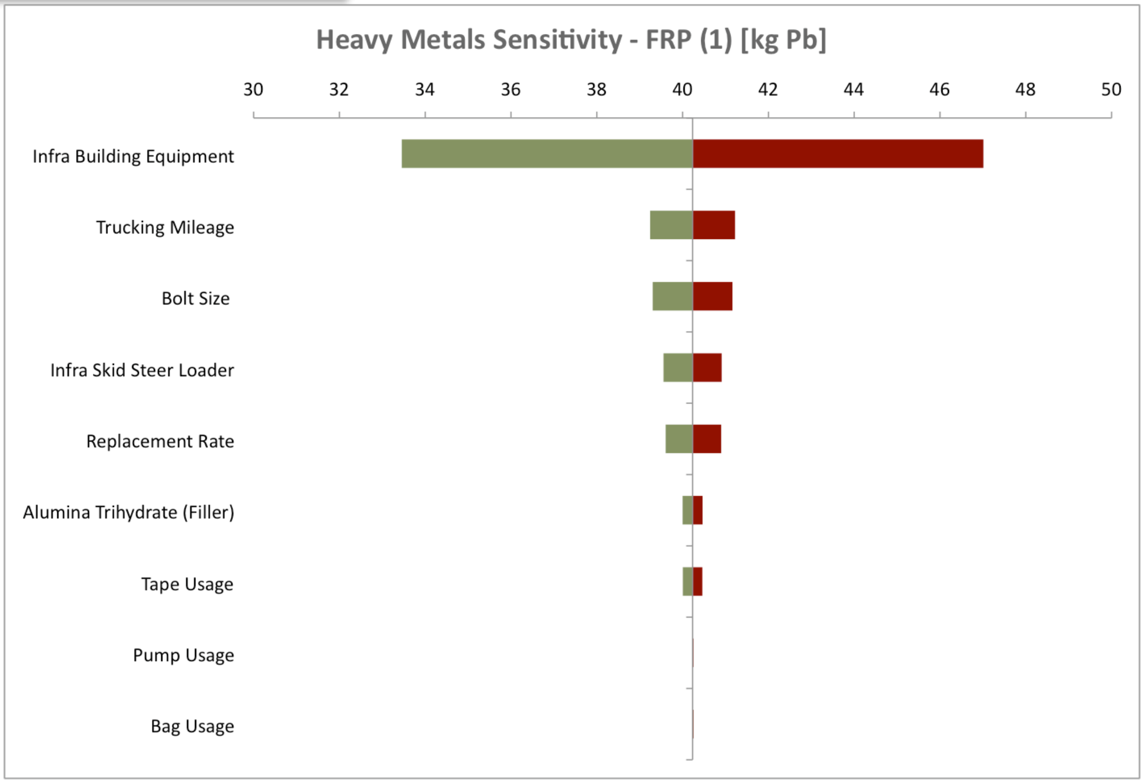
Acidification Sensitivity - FRP (1) [kg PO4]
9500
9700
9900
10100
10300
10500
10700
10900
Bolt Size
Alumina Trihydrate (Filler)
Infra Building Equipment
Replacement Rate
Trucking Mileage
Tape Usage
Infra Skid Steer Loader
Pump Usage
Bag Usage

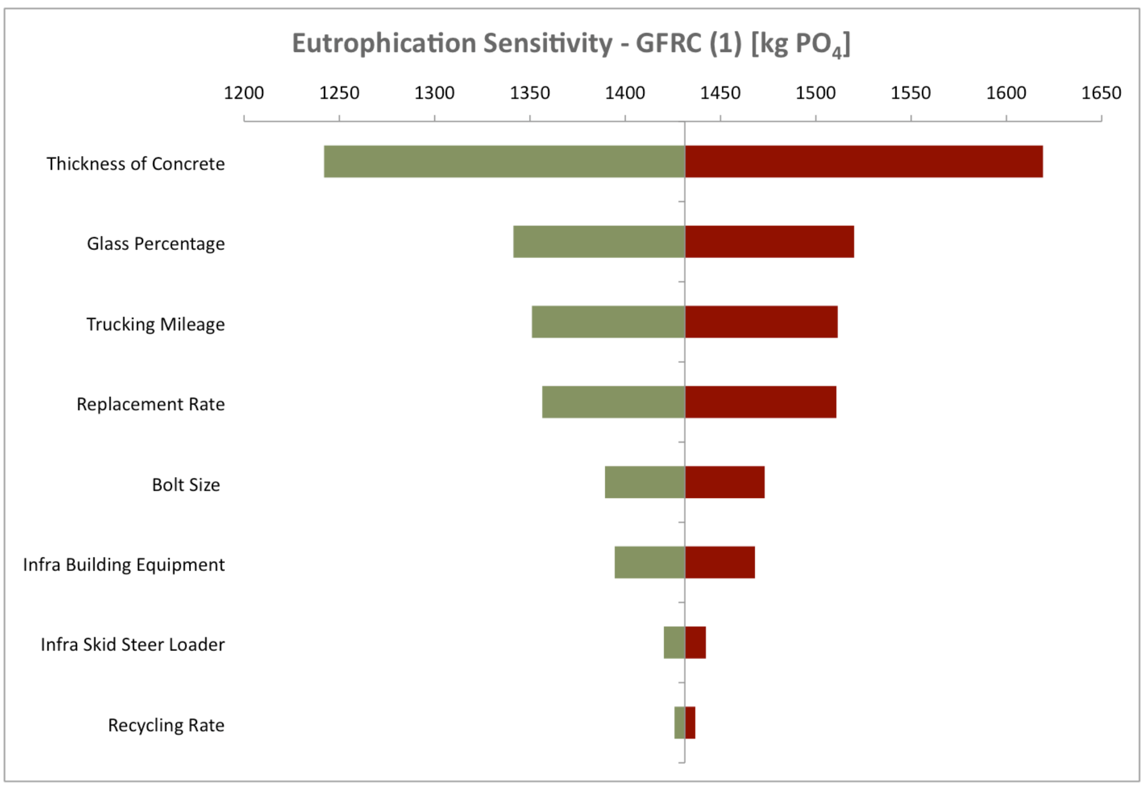


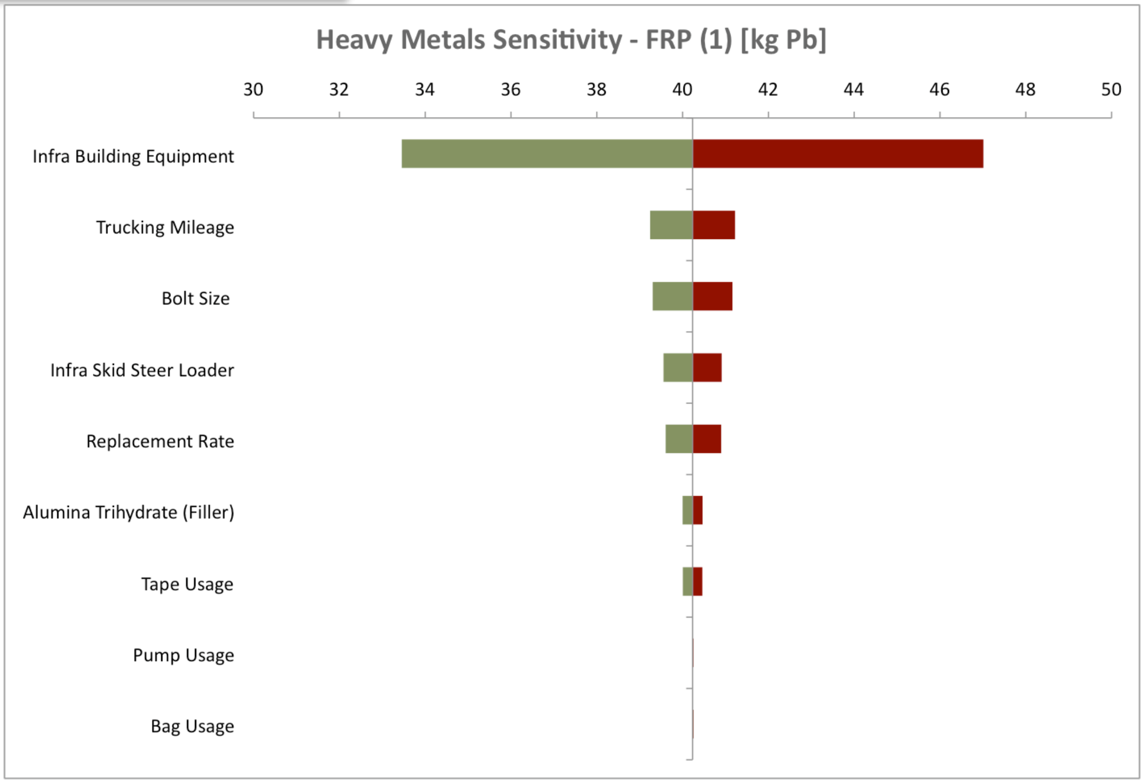
Acidification Sensitivity - GFRC (1) [kg PO4]
15500
16500
17500
18500
19500
20500
21500
Trucking Mileage
Thickness of Concrete
Replacement Rate
Infra Building Equipment
Bolt Size
Glass Percentage
Infra Skid Steer Loader
Recycling Rate

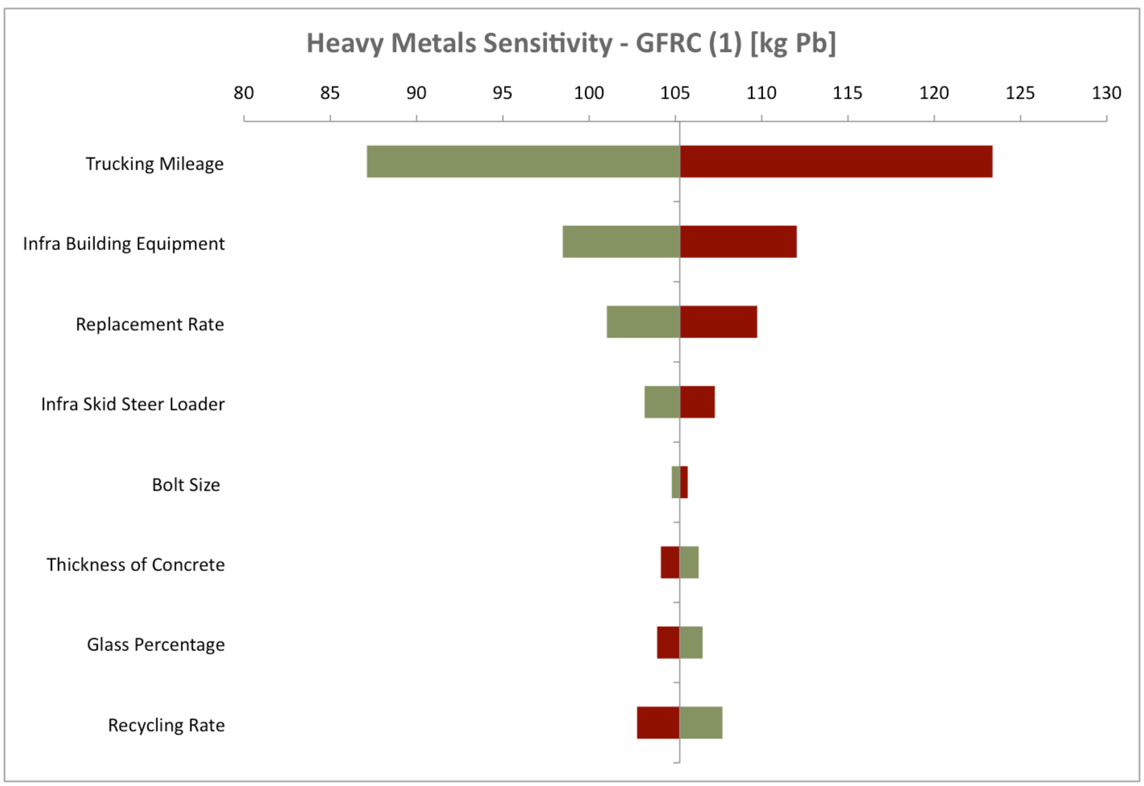

Eutrophication Sensitivity - FRP (1) [kg PO_4]
580
600
620
640
660
680
700
Bolt Size
Infra Building Equipment
Replacement Rate
Alumina Trihydrate (Filler)
Trucking Mileage
Infra Skid Steer Loader
Tape Usage
Pump Usage
Bag Usage

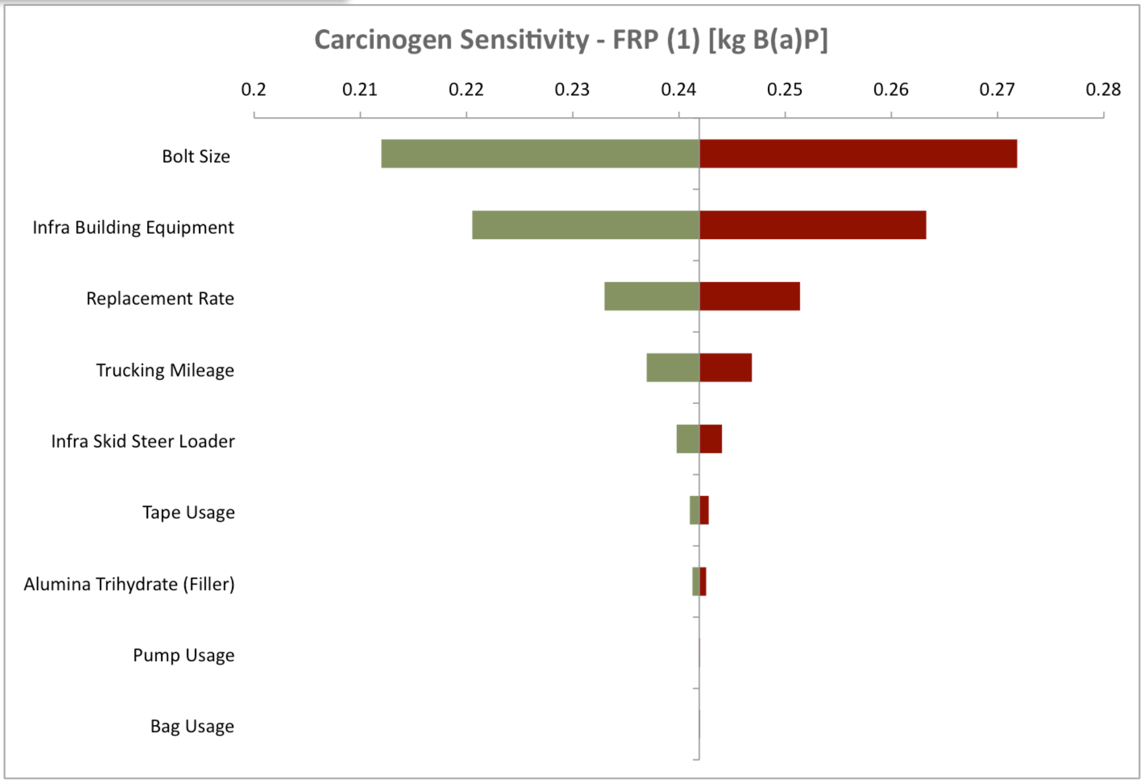

Eutrophication Sensitivity - GFRC (1) [kg PO_4]
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
Thickness of Concrete
Glass Percentage
Trucking Mileage
Replacement Rate
Bolt Size
Infra Building Equipment
Infra Skid Steer Loader
Recycling Rate


Heavy Metals Sensitivity - FRP (1) [kg Pb]
30
32
34
36
38
40
42
44
46
48
50
Infra Building Equipment
Trucking Mileage
Bolt Size
Infra Skid Steer Loader
Replacement Rate
Alumina Trihydrate (Filler)
Tape Usage
Pump Usage
Bag Usage

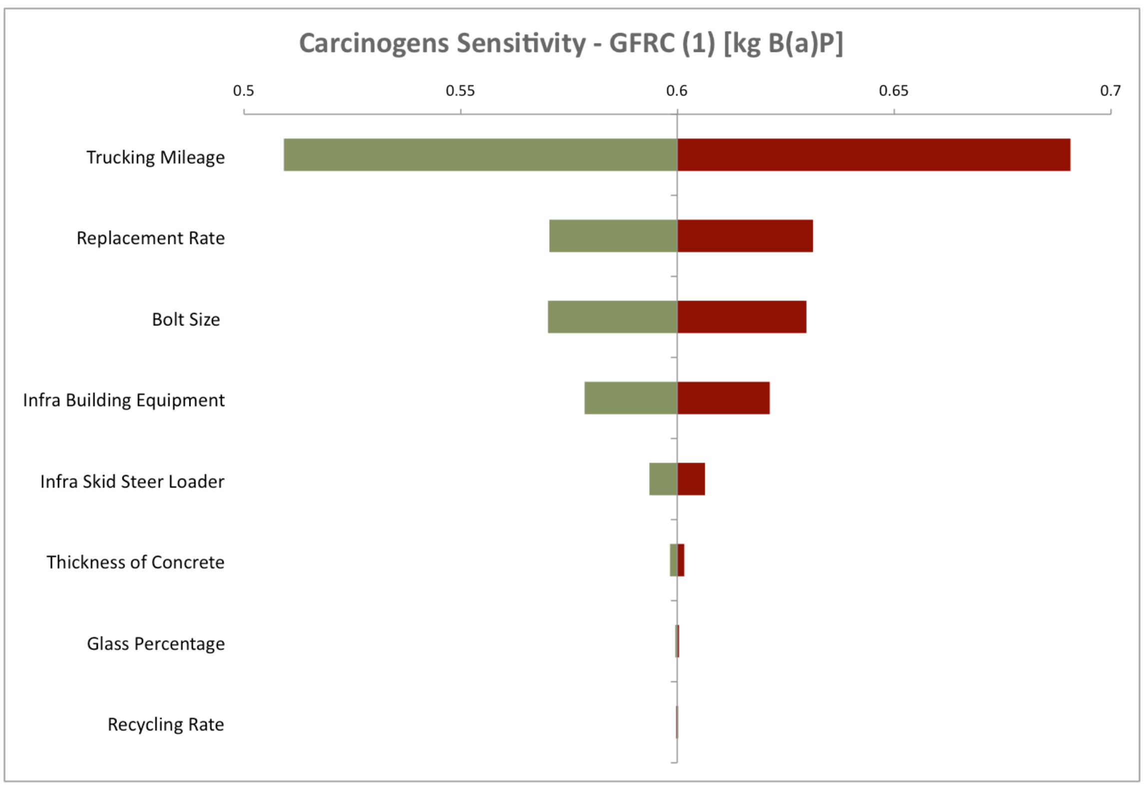

Eutrophication Sensitivity - GFRC (1) [kg PO4]
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
Thickness of Concrete
Glass Percentage
Trucking Mileage
Replacement Rate
Bolt Size
Infra Building Equipment
Infra Skid Steer Loader
Recycling Rate


Heavy Metals Sensitivity - FRP (1) [kg Pb]
30
32
34
36
38
40
42
44
46
48
50
Infra Building Equipment
Trucking Mileage
Bolt Size
Infra Skid Steer Loader
Replacement Rate
Alumina Trihydrate (Filler)
Tape Usage
Pump Usage
Bag Usage

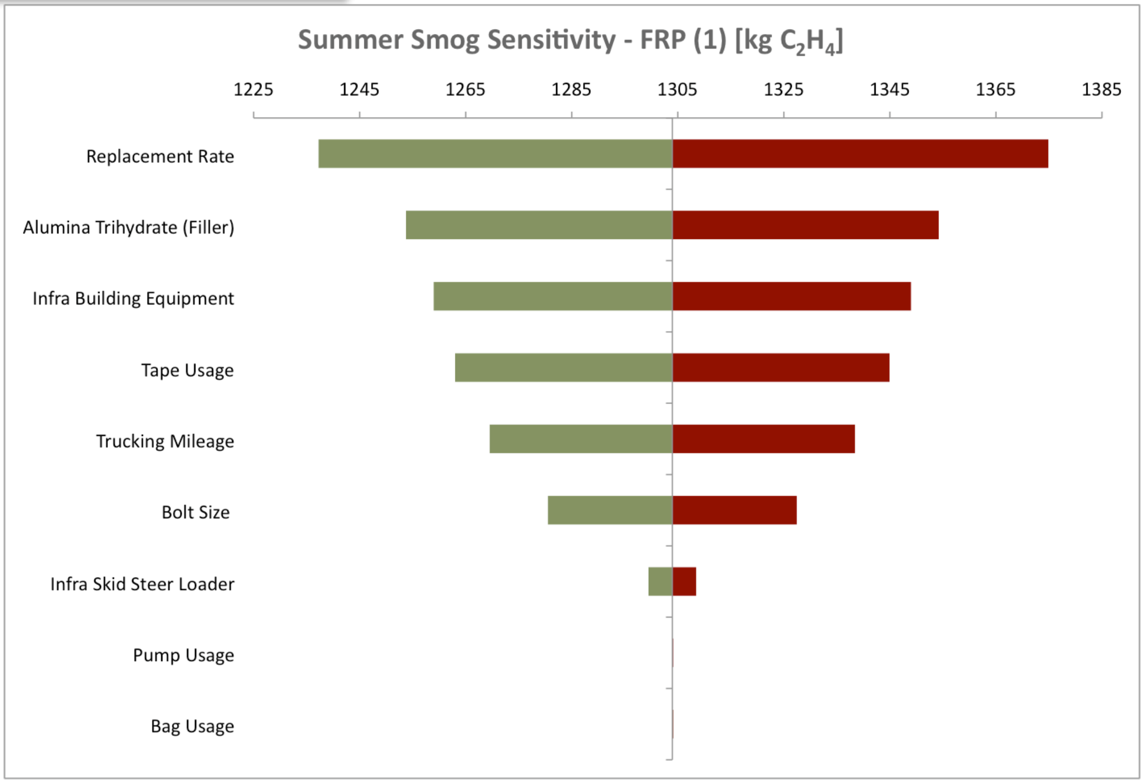

Heavy Metals Sensitivity - GFRC (1) [kg Pb]
80
85
90
95
100
105
110
115
120
125
130
Trucking Mileage
Infra Building Equipment
Replacement Rate
Infra Skid Steer Loader
Bolt Size
Thickness of Concrete
Glass Percentage
Recycling Rate

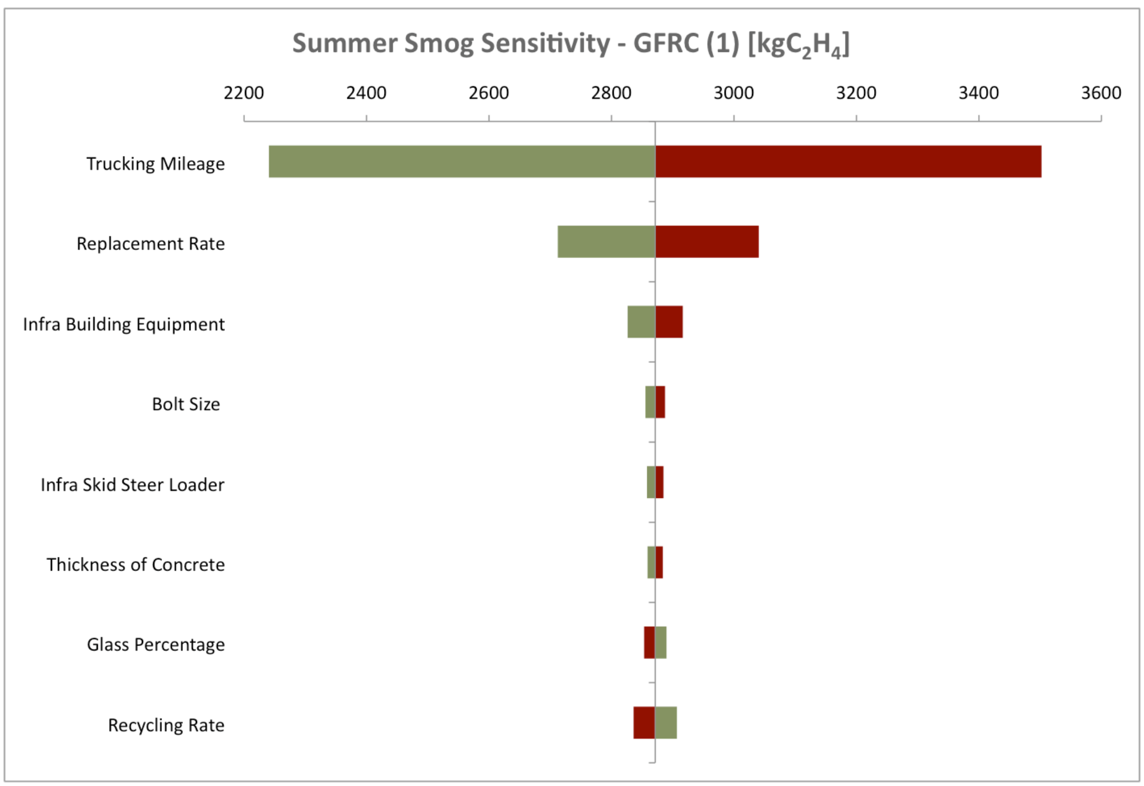


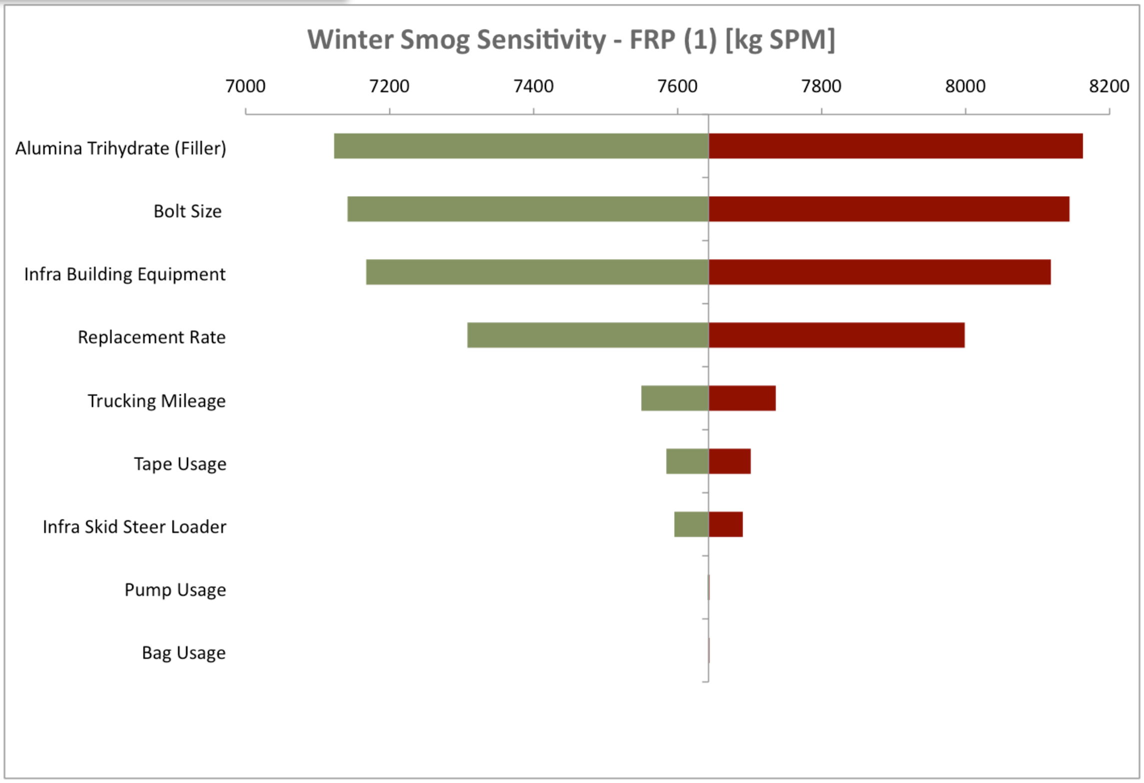
Carcinogen Sensitivity - FRP (1) [kg B(a)P]
0.2
0.21
0.22
0.23
0.24
0.25
0.26
0.27
0.28
Bolt Size
Infra Building Equipment
Replacement Rate
Trucking Mileage
Infra Skid Steer Loader
Tape Usage
Alumina Trihydrate (Filler)
Pump Usage
Bag Usage

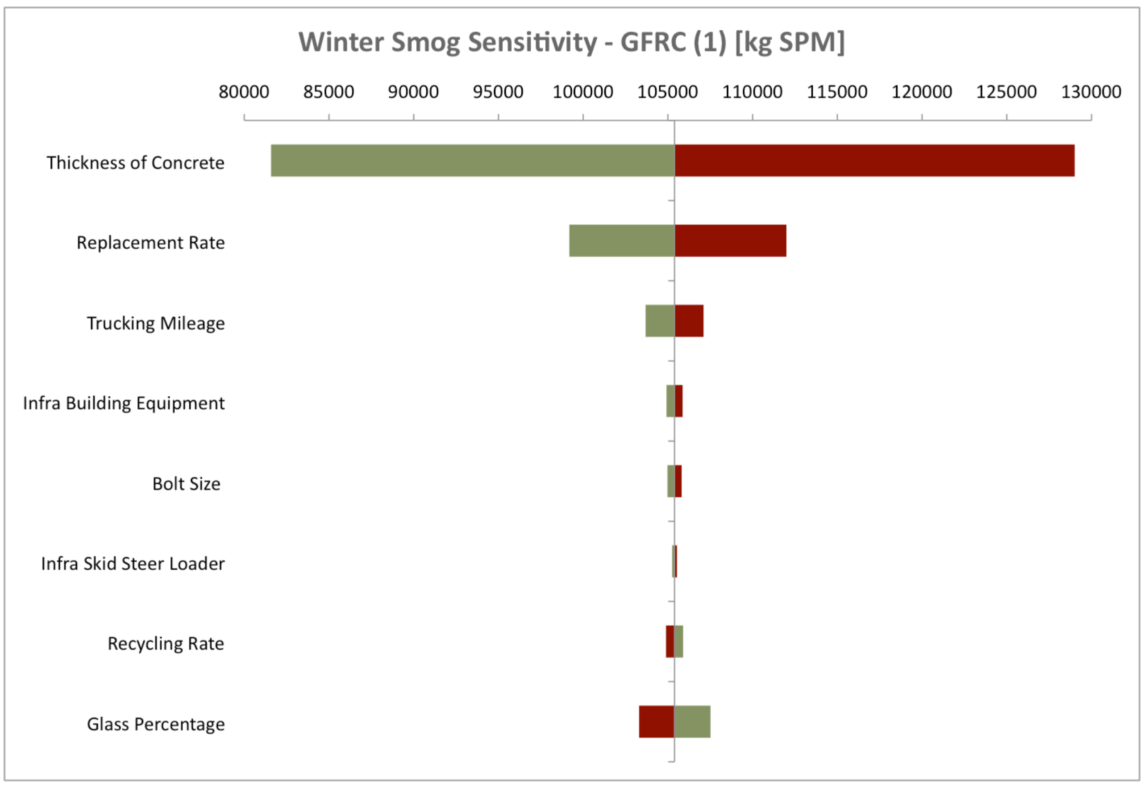


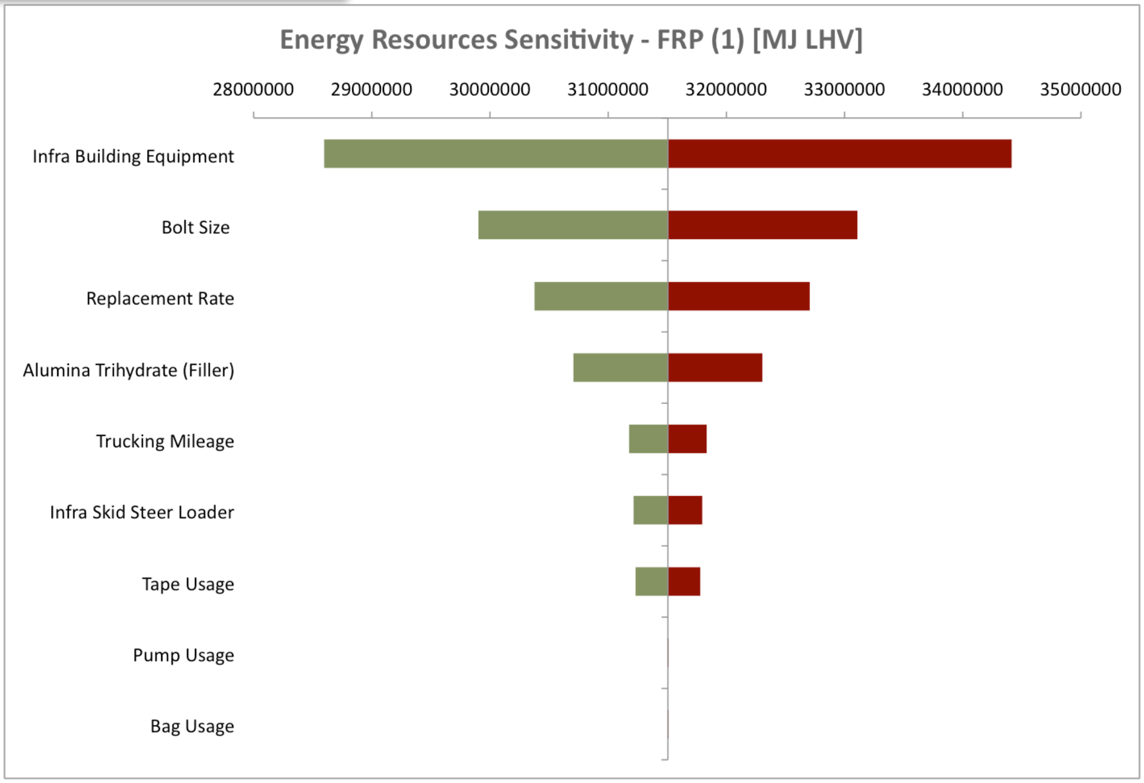
Carcinogens Sensitivity - GFRC (1) [kg B(a)P]
0.5
0.55
0.6
0.65
0.7
Trucking Mileage
Replacement Rate
Bolt Size
Infra Building Equipment
Infra Skid Steer Loader
Thickness of Concrete
Glass Percentage
Recycling Rate

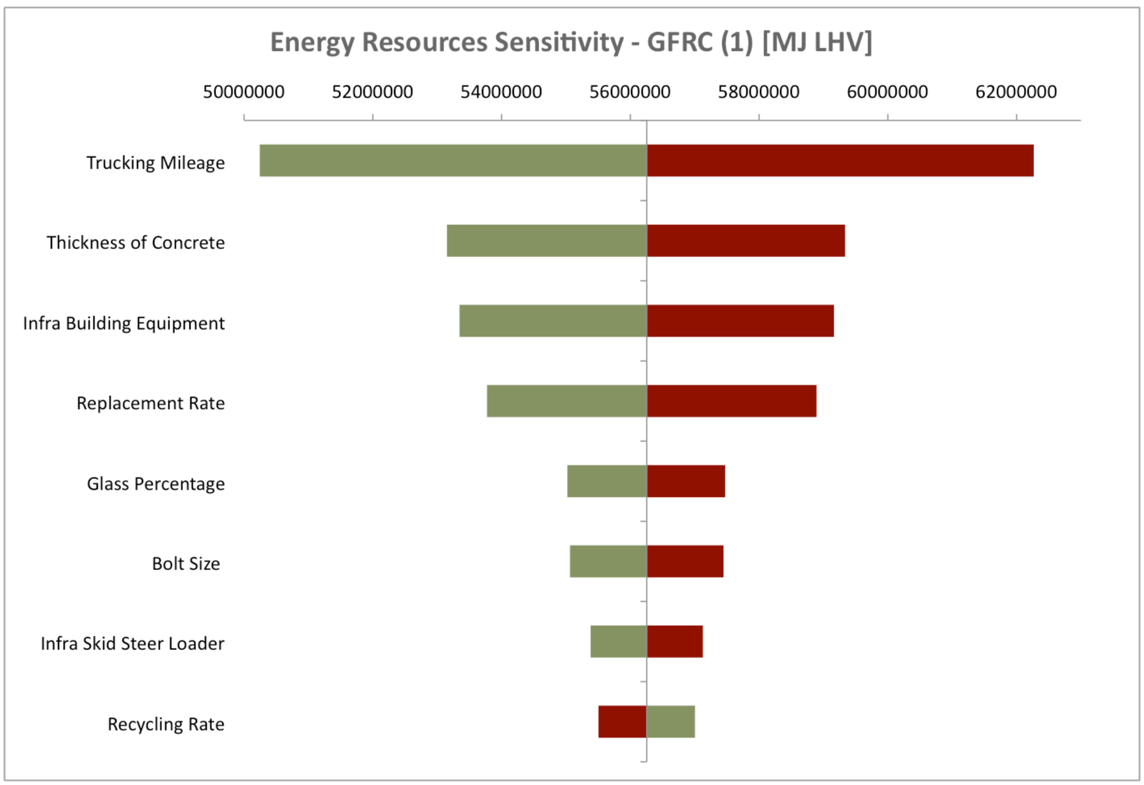

Summer Smog Sensitivity - FRP (1) [kg C_2H_4]
1225
1245
1265
1285
1305
1325
1345
1365
1385
Replacement Rate
Alumina Trihydrate (Filler)
Infra Building Equipment
Tape Usage
Trucking Mileage
Bolt Size
Infra Skid Steer Loader
Pump Usage
Bag Usage


Summer Smog Sensitivity - GFRC (1) [kgC_2H_4]
2200
2400
2600
2800
3000
3200
3400
3600
Trucking Mileage
Replacement Rate
Infra Building Equipment
Bolt Size
Infra Skid Steer Loader
Thickness of Concrete
Glass Percentage
Recycling Rate

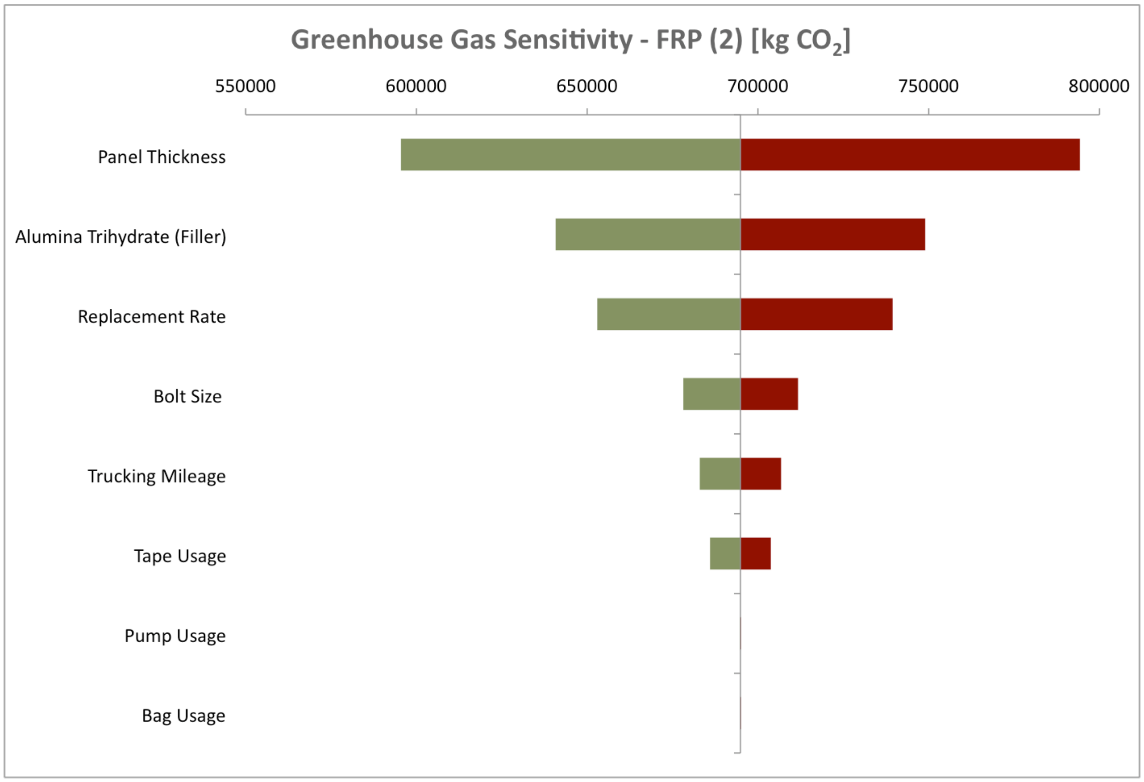

Winter Smog Sensitivity - FRP (1) [kg SPM]
7000
7200
7400
7600
7800
8000
8200
Alumina Trihydrate (Filler)
Bolt Size
Infra Building Equipment
Replacement Rate
Trucking Mileage
Tape Usage
Infra Skid Steer Loader
Pump Usage
Bag Usage

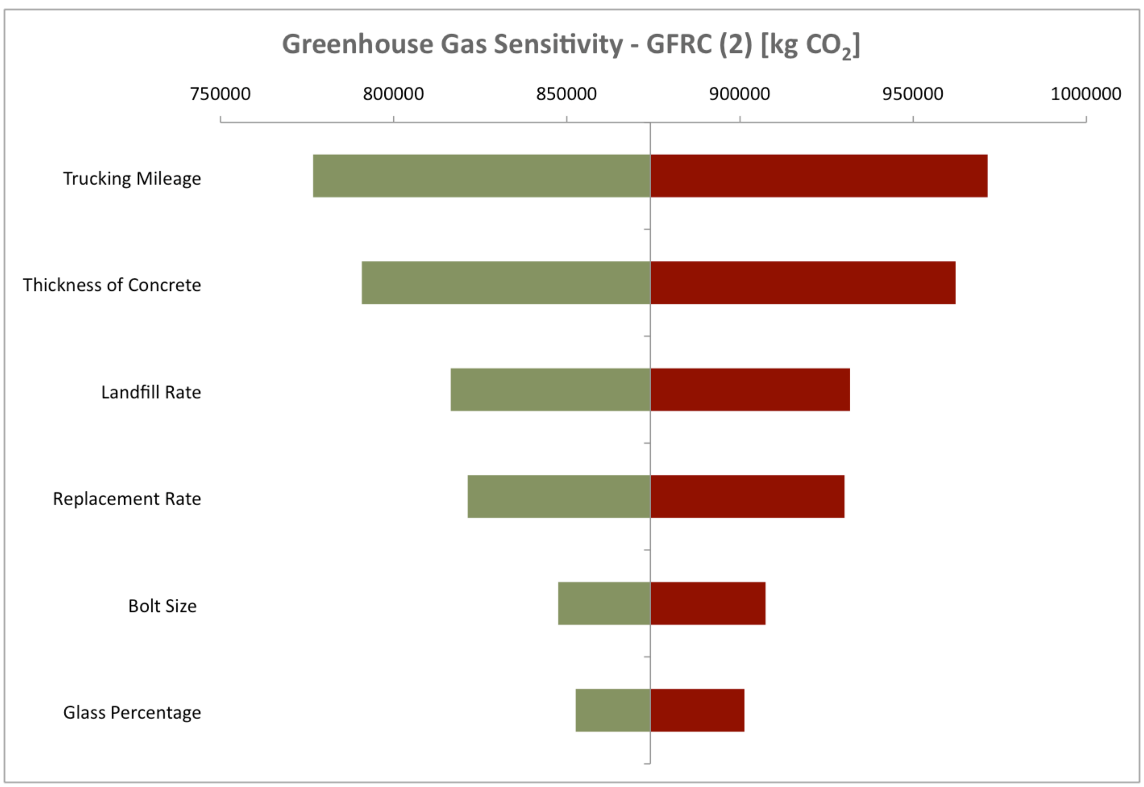

Winter Smog Sensitivity - GFRC (1) [kg SPM]
80000
85000
90000
95000
100000
105000
110000
115000
120000
125000
130000
Thickness of Concrete
Replacement Rate
Trucking Mileage
Infra Building Equipment
Bolt Size
Infra Skid Steer Loader
Recycling Rate
Glass Percentage

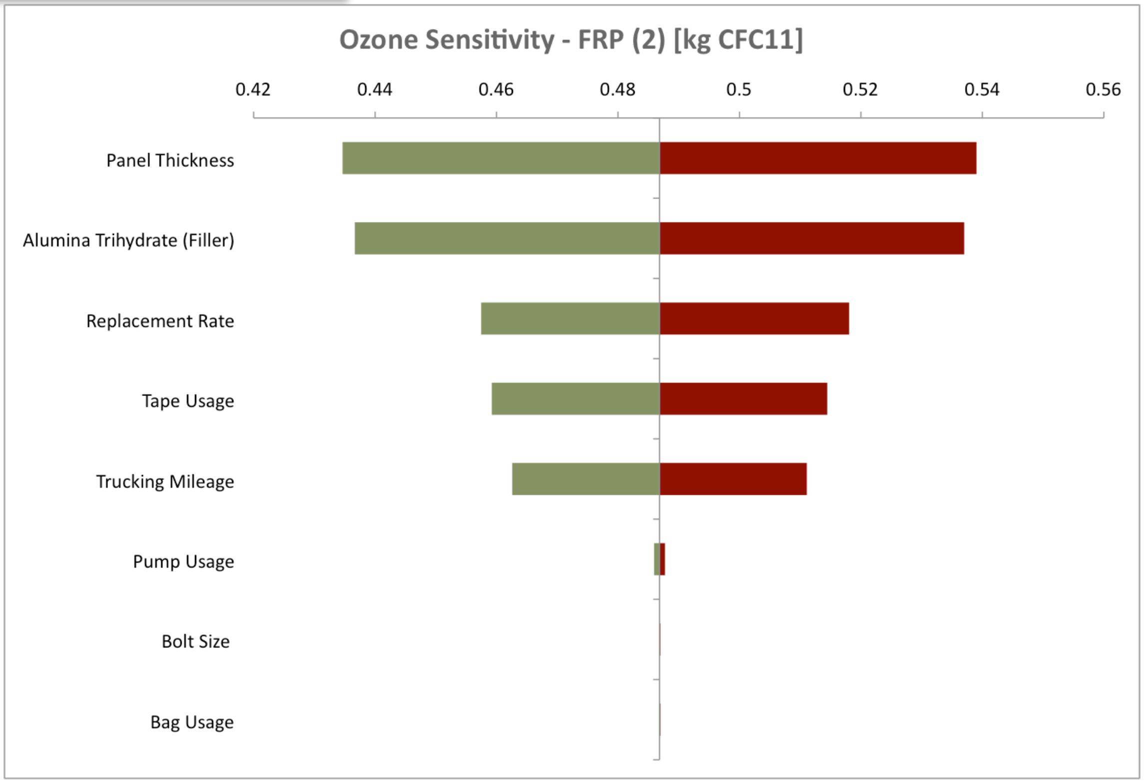

Energy Resources Sensitivity - FRP (1) [MJ LHV]
28000000
29000000
30000000
31000000
32000000
33000000
34000000
35000000
Infra Building Equipment
Bolt Size
Replacement Rate
Alumina Trihydrate (Filler)
Trucking Mileage
Infra Skid Steer Loader
Tape Usage
Pump Usage
Bag Usage

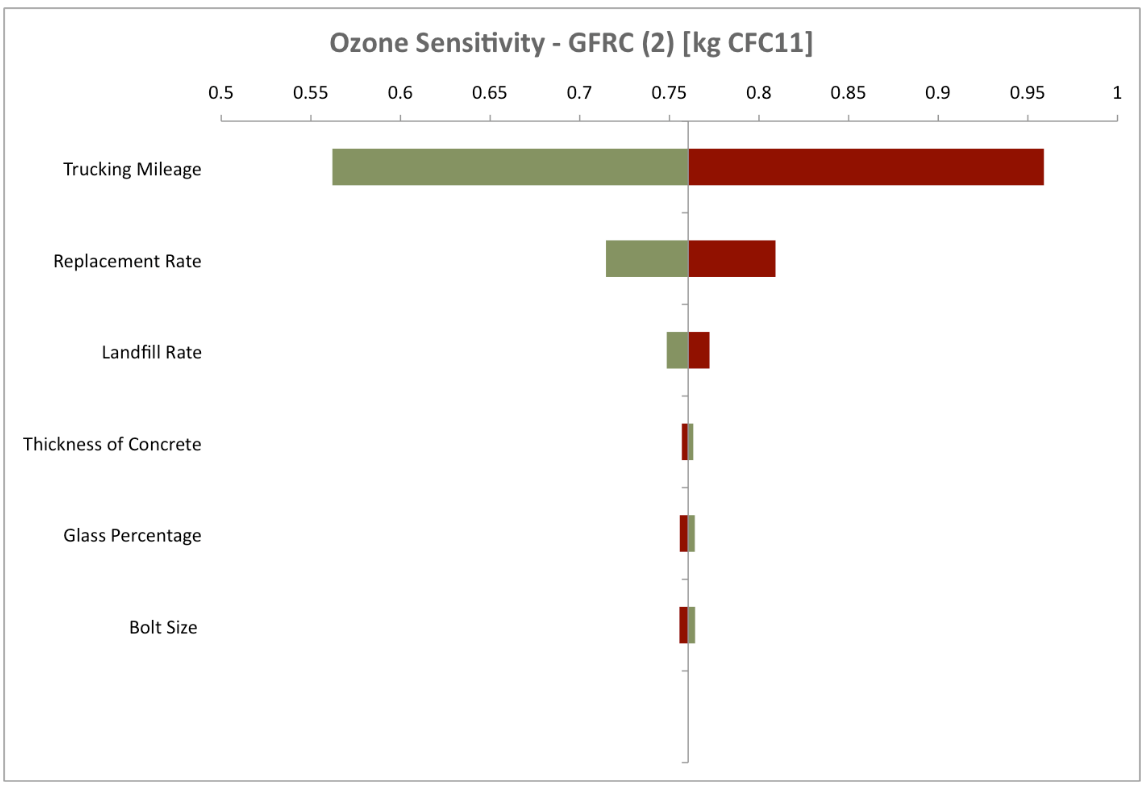

Energy Resources Sensitivity - GFRC (1) [MJ LHV]
50000000
52000000
54000000
56000000
58000000
60000000
62000000
Trucking Mileage
Thickness of Concrete
Infra Building Equipment
Replacement Rate
Glass Percentage
Bolt Size
Infra Skid Steer Loader
Recycling Rate

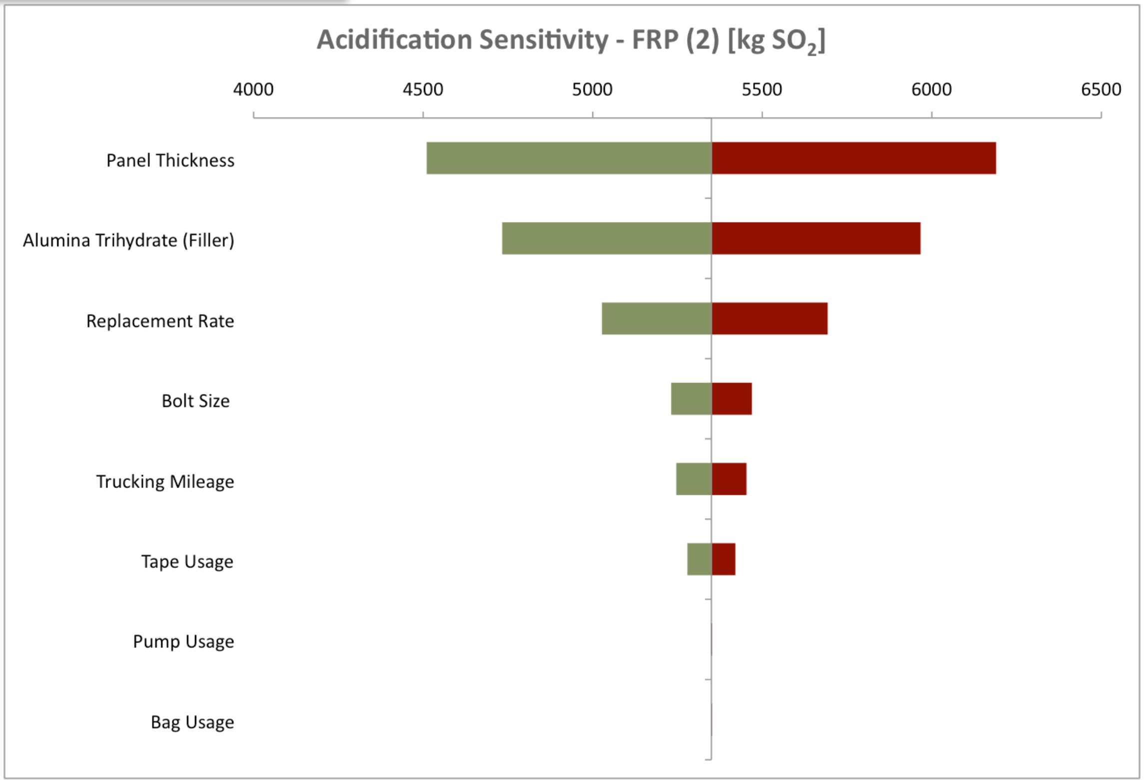
Appendix D: Final Sensitivity Analysis Results

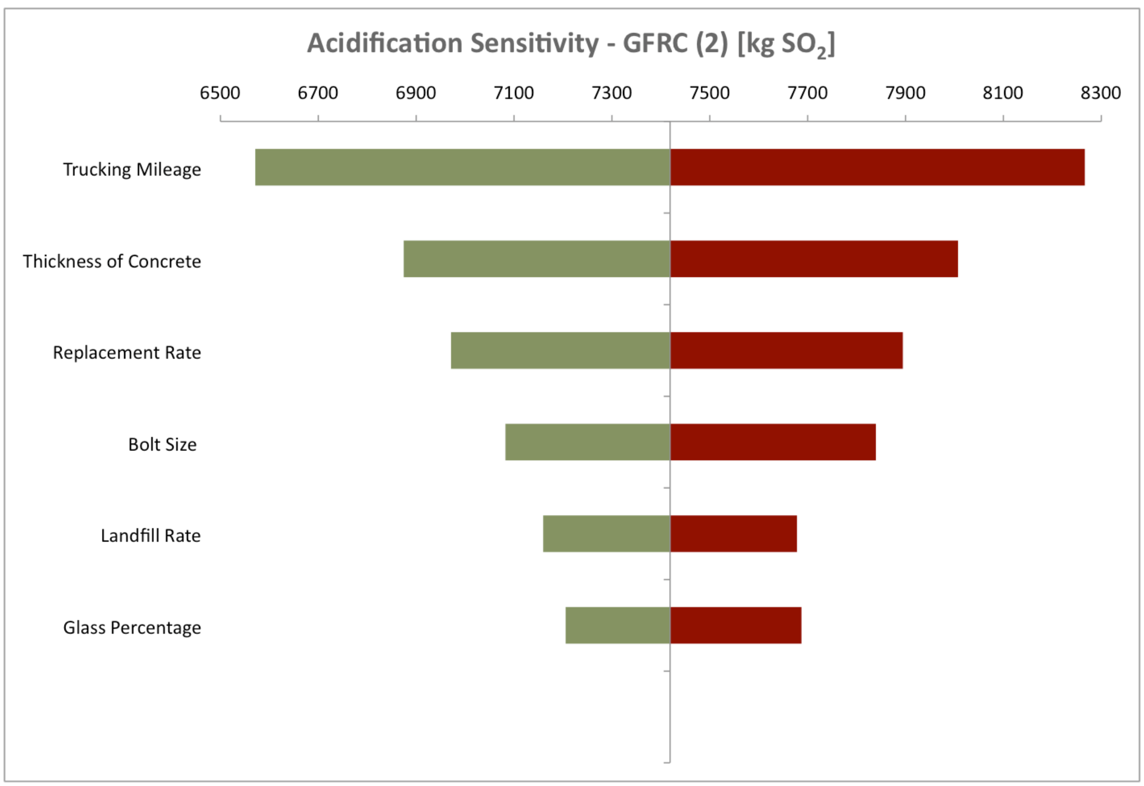


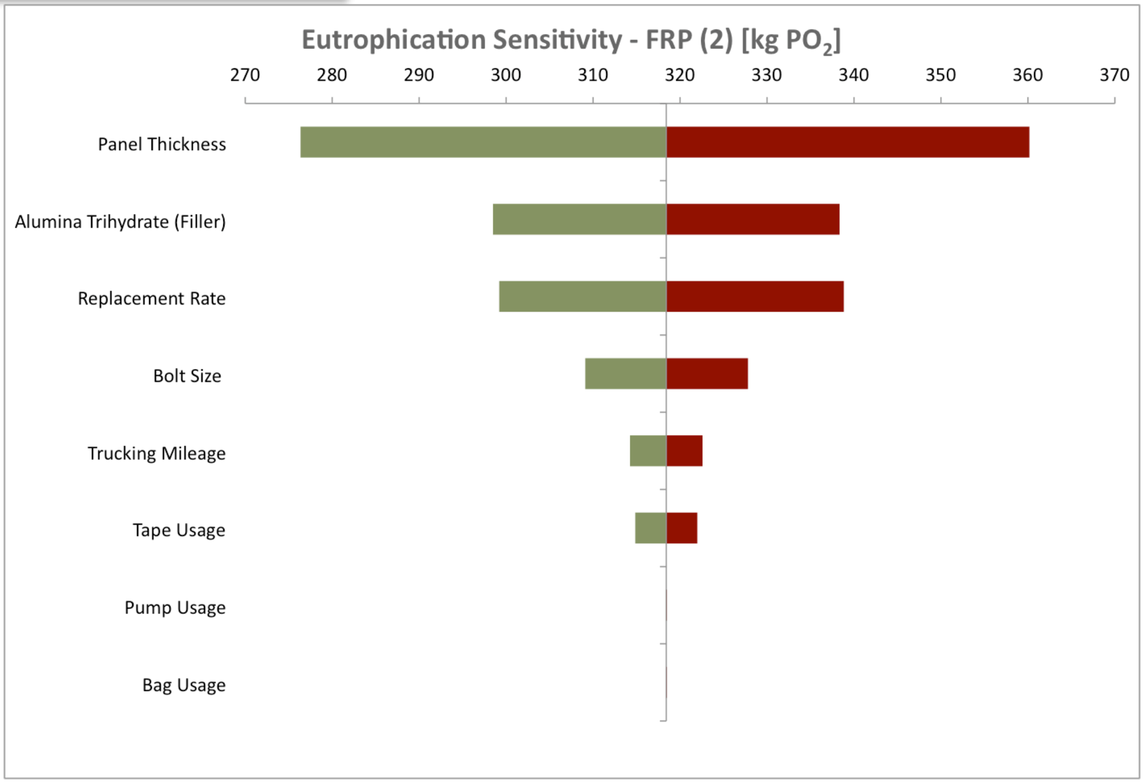


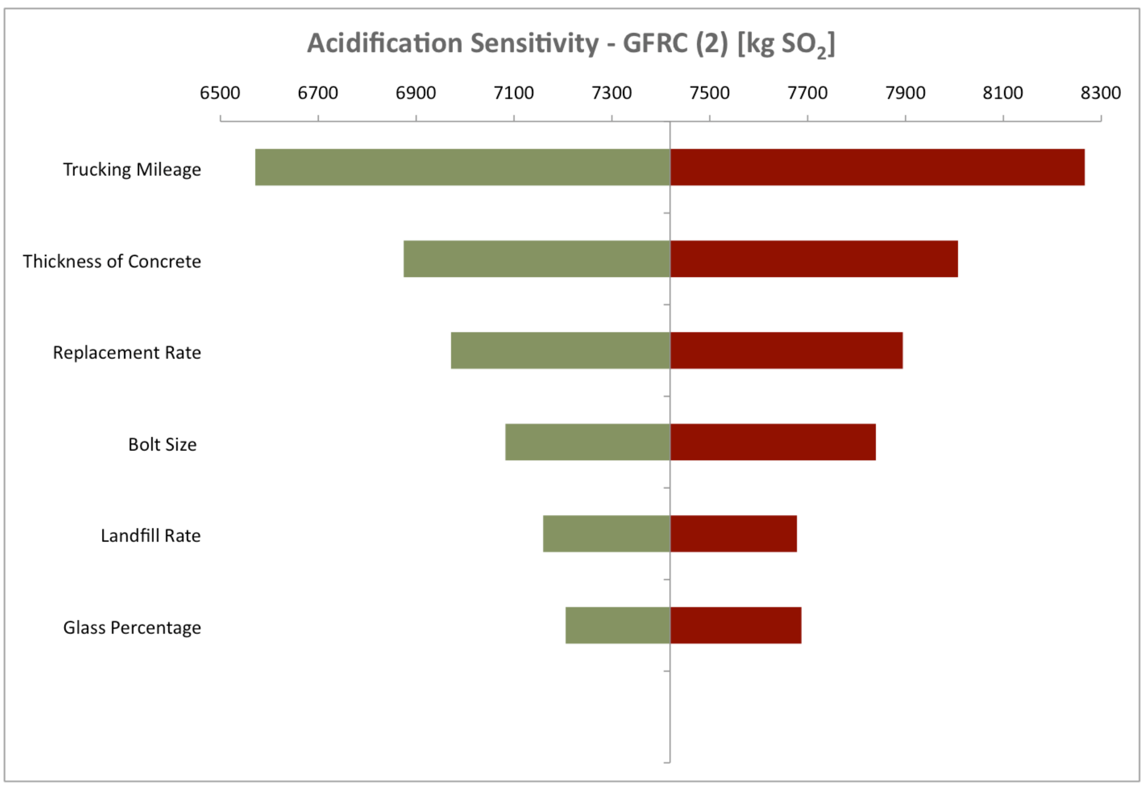

Ozone Sensitivity - FRP (2) [kg CFC11]
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56
Panel Thickness
Alumina Trihydrate (Filler)
Replacement Rate
Tape Usage
Trucking Mileage
Pump Usage
Bolt Size
Bag Usage

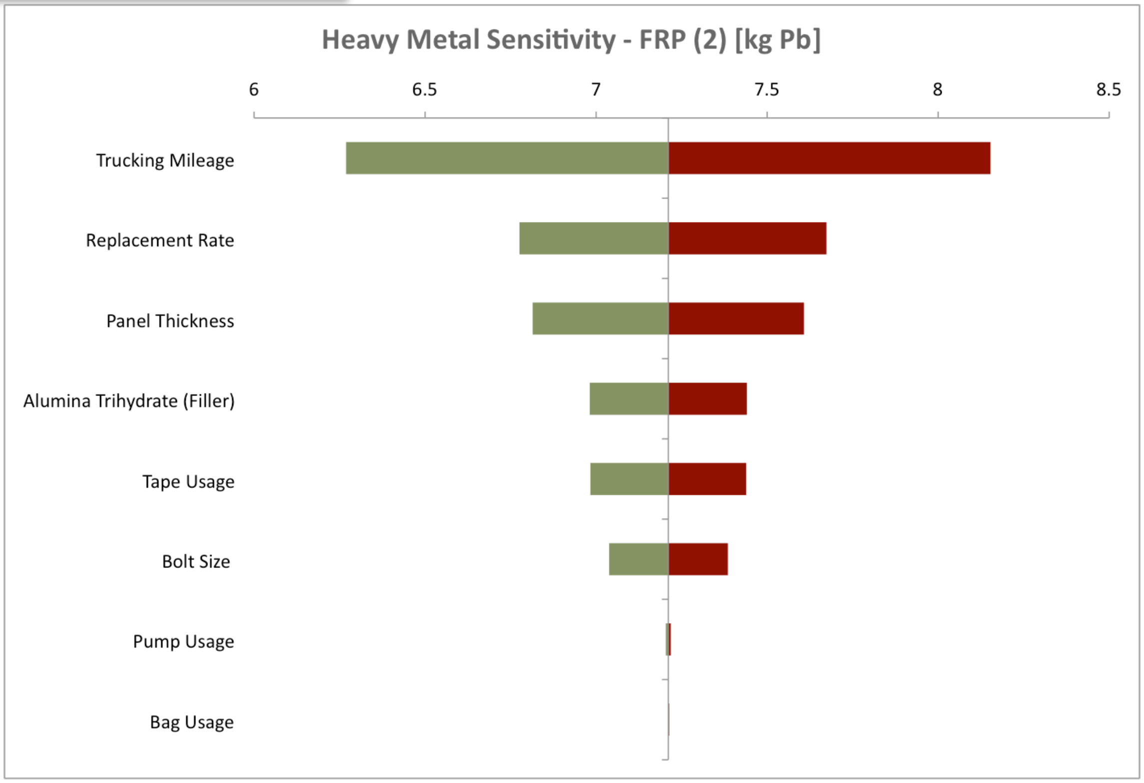

Ozone Sensitivity - GFRC (2) [kg CFC11]
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
Trucking Mileage
Replacement Rate
Landfill Rate
Thickness of Concrete
Glass Percentage
Bolt Size

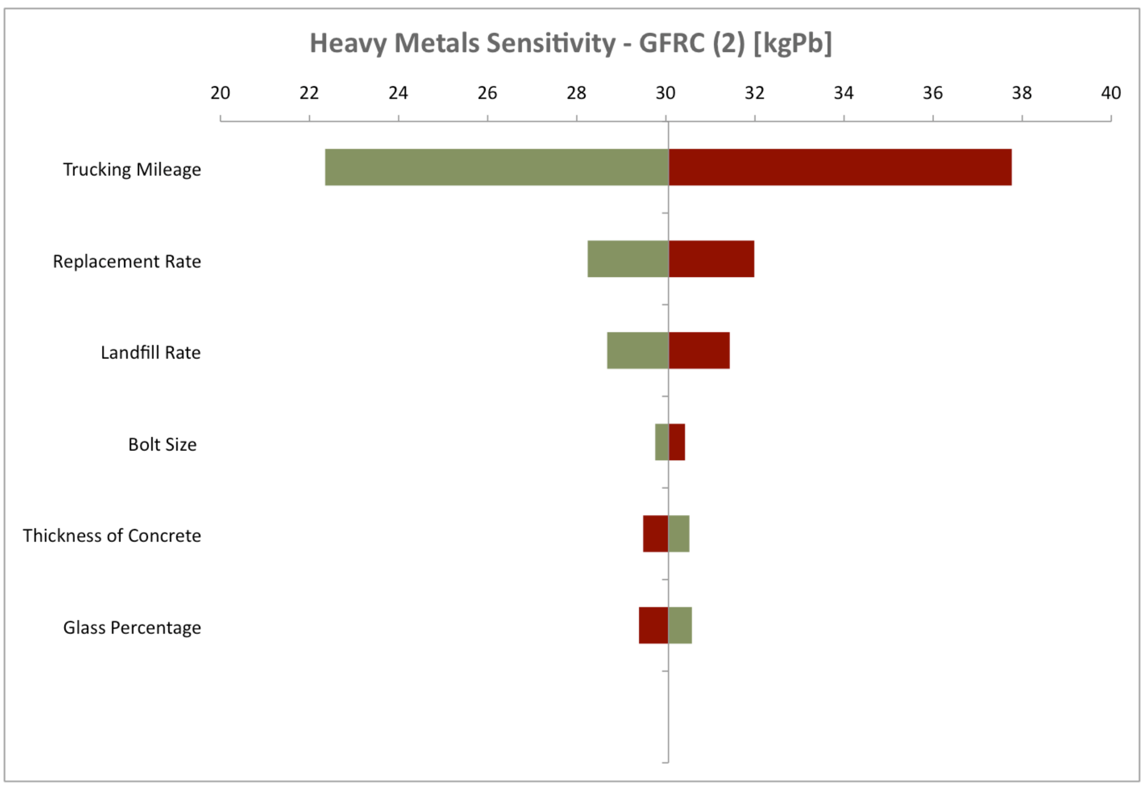

Acidification Sensitivity - FRP (2) [kg SO2]
4000
4500
5000
5500
6000
6500
Panel Thickness
Alumina Trihydrate (Filler)
Replacement Rate
Bolt Size
Trucking Mileage
Tape Usage
Pump Usage
Bag Usage

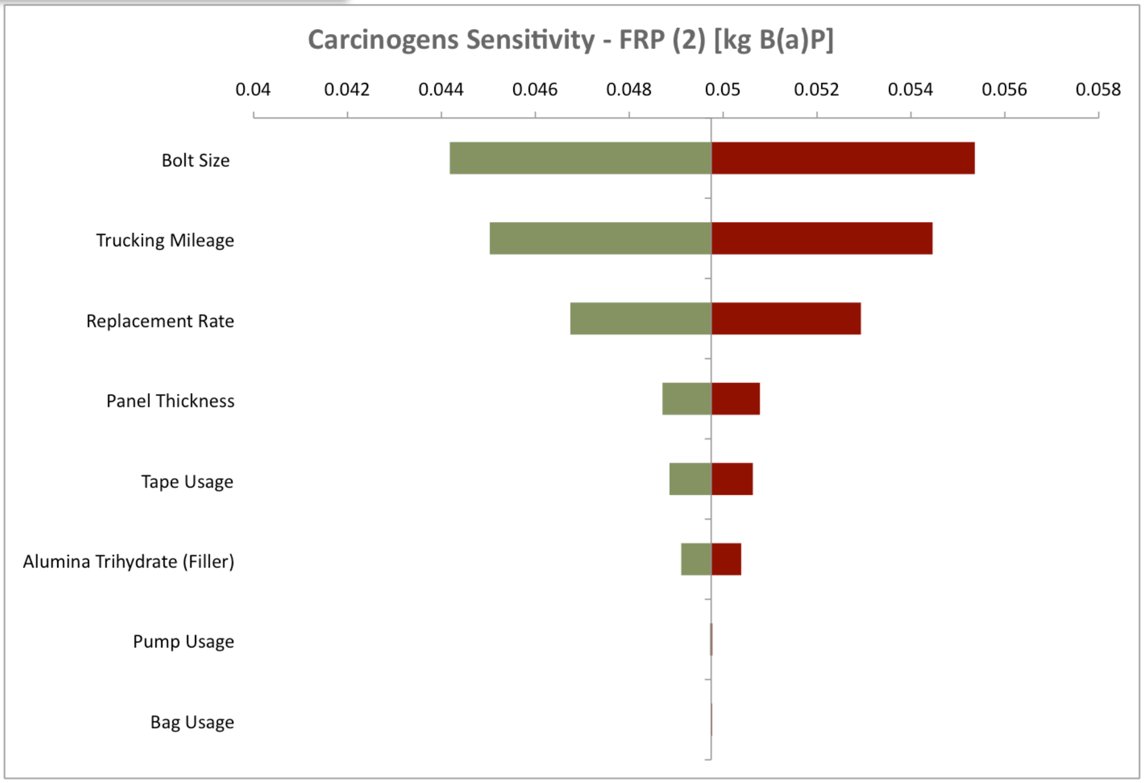

Acidification Sensitivity - GFRC (2) [kg SO2]
6500
6700
6900
7100
7300
7500
7700
7900
8100
8300
Trucking Mileage
Thickness of Concrete
Replacement Rate
Bolt Size
Landfill Rate
Glass Percentage

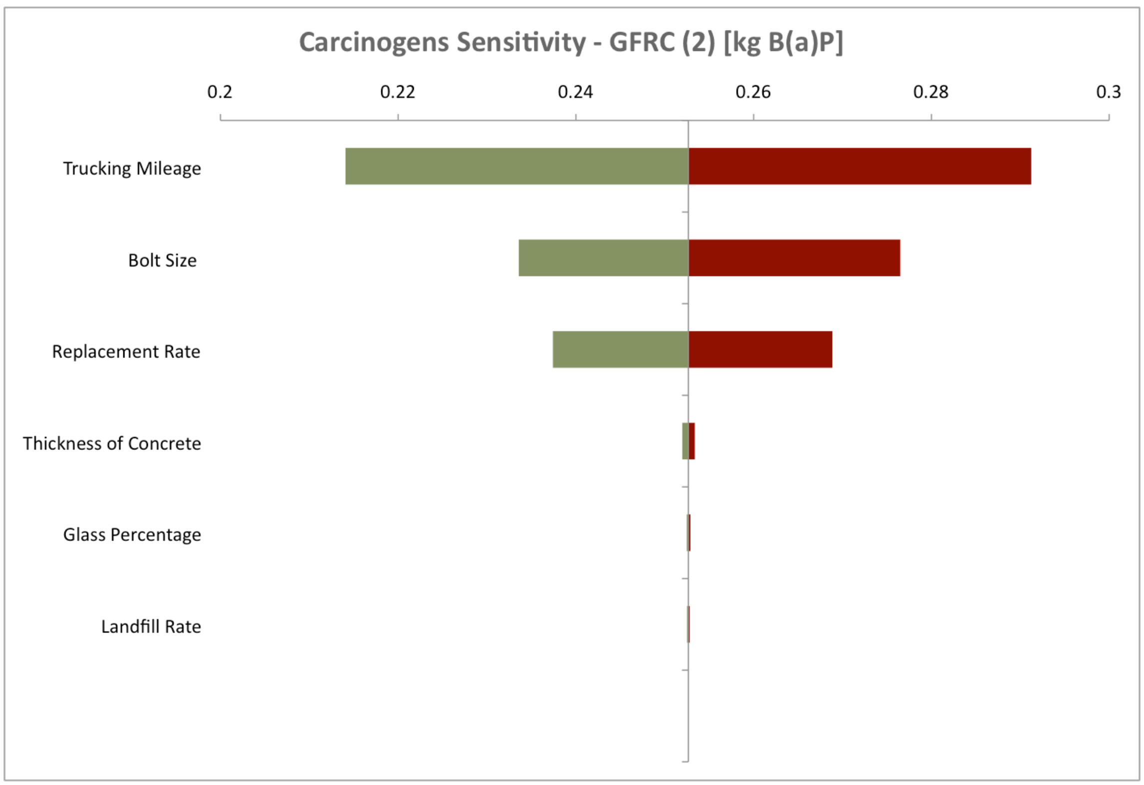

Eutrophication Sensitivity - FRP (2) [kg PO2]
270
280
290
300
310
320
330
340
350
360
370
Panel Thickness
Alumina Trihydrate (Filler)
Replacement Rate
Bolt Size
Trucking Mileage
Tape Usage
Pump Usage
Bag Usage

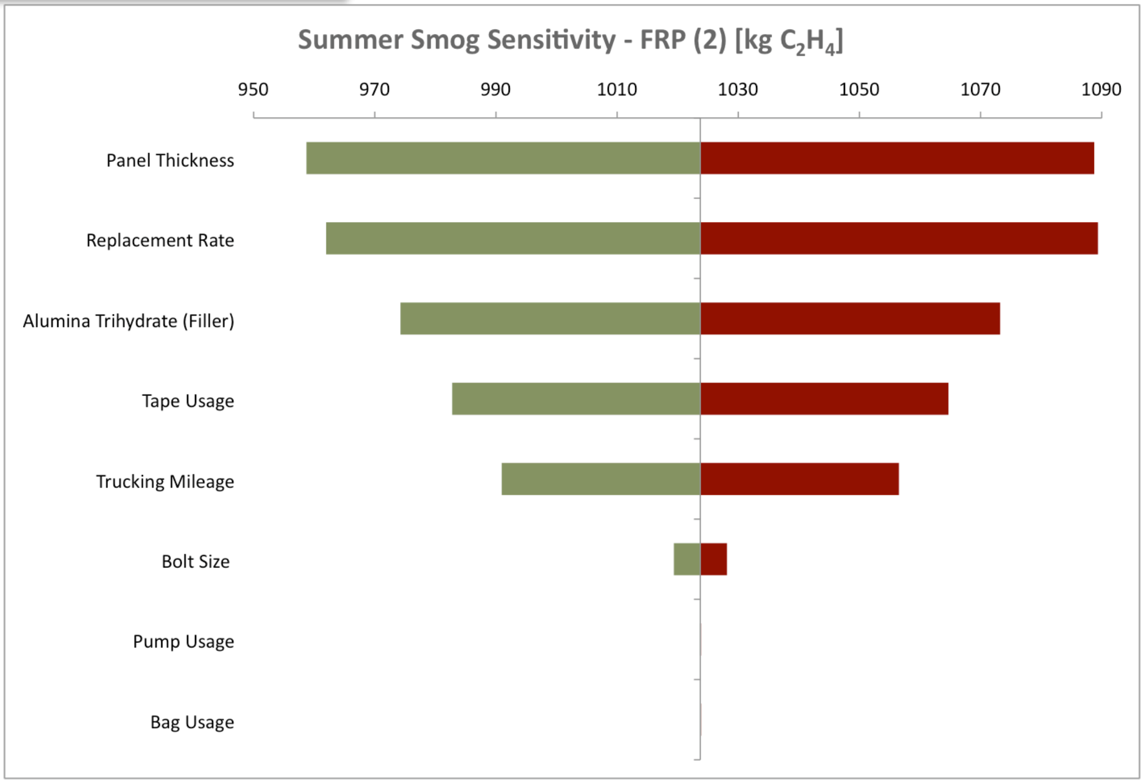

Acidification Sensitivity - GFRC (2) [kg SO2]
6500
6700
6900
7100
7300
7500
7700
7900
8100
8300
Trucking Mileage
Thickness of Concrete
Replacement Rate
Bolt Size
Landfill Rate
Glass Percentage

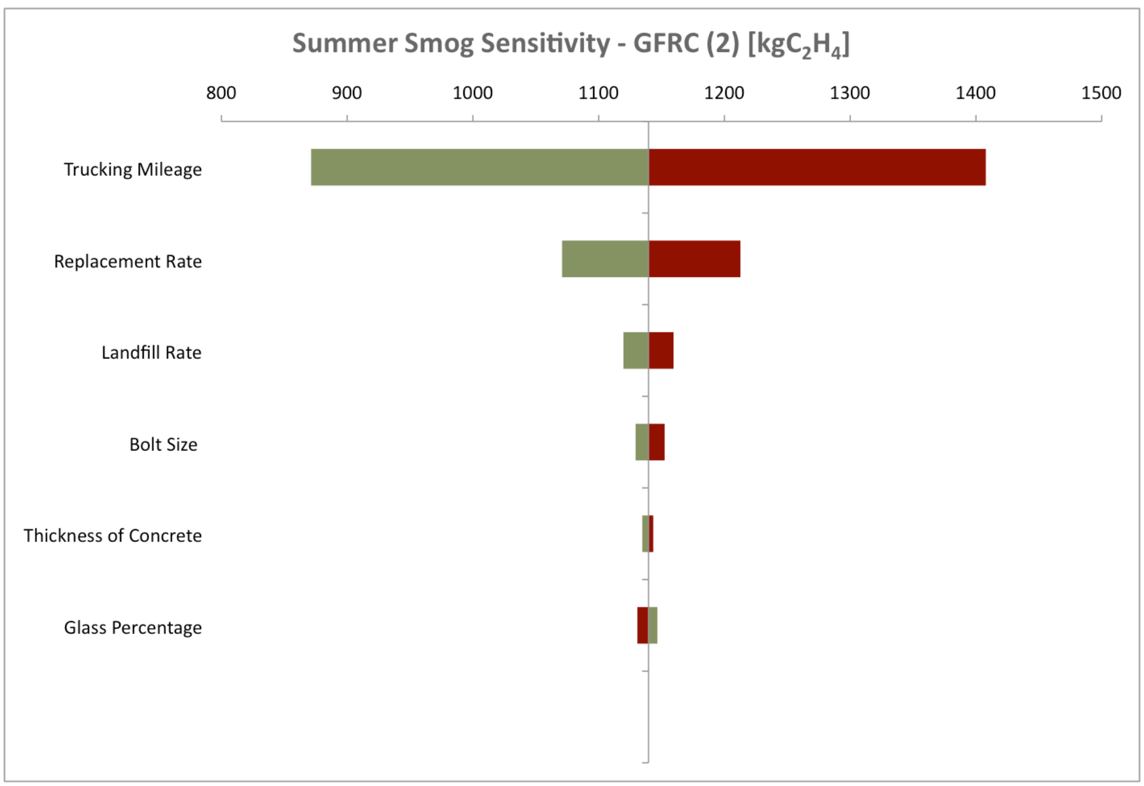

Heavy Metal Sensitivity - FRP (2) [kg Pb]
6
6.5
7
7.5
8
8.5
Trucking Mileage
Replacement Rate
Panel Thickness
Alumina Trihydrate (Filler)
Tape Usage
Bolt Size
Pump Usage
Bag Usage

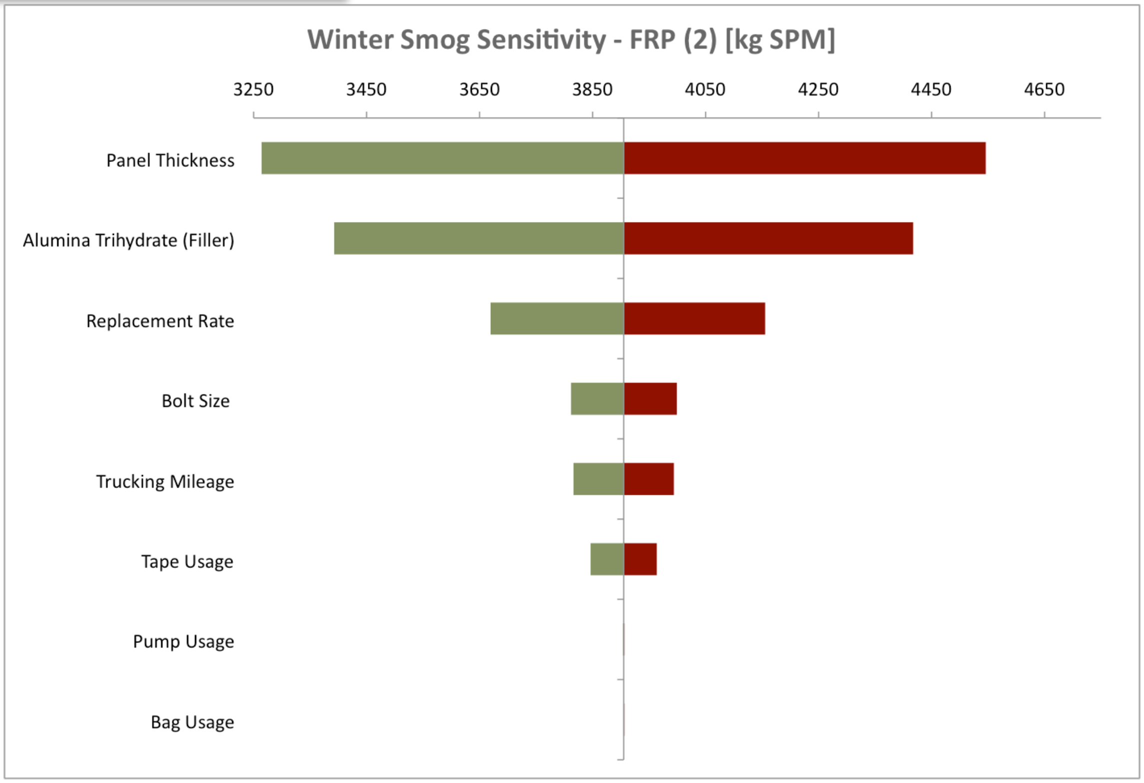

Heavy Metals Sensitivity - GFRC (2) [kgPb]
20
22
24
26
28
30
32
34
36
38
40
Trucking Mileage
Replacement Rate
Landfill Rate
Bolt Size
Thickness of Concrete
Glass Percentage

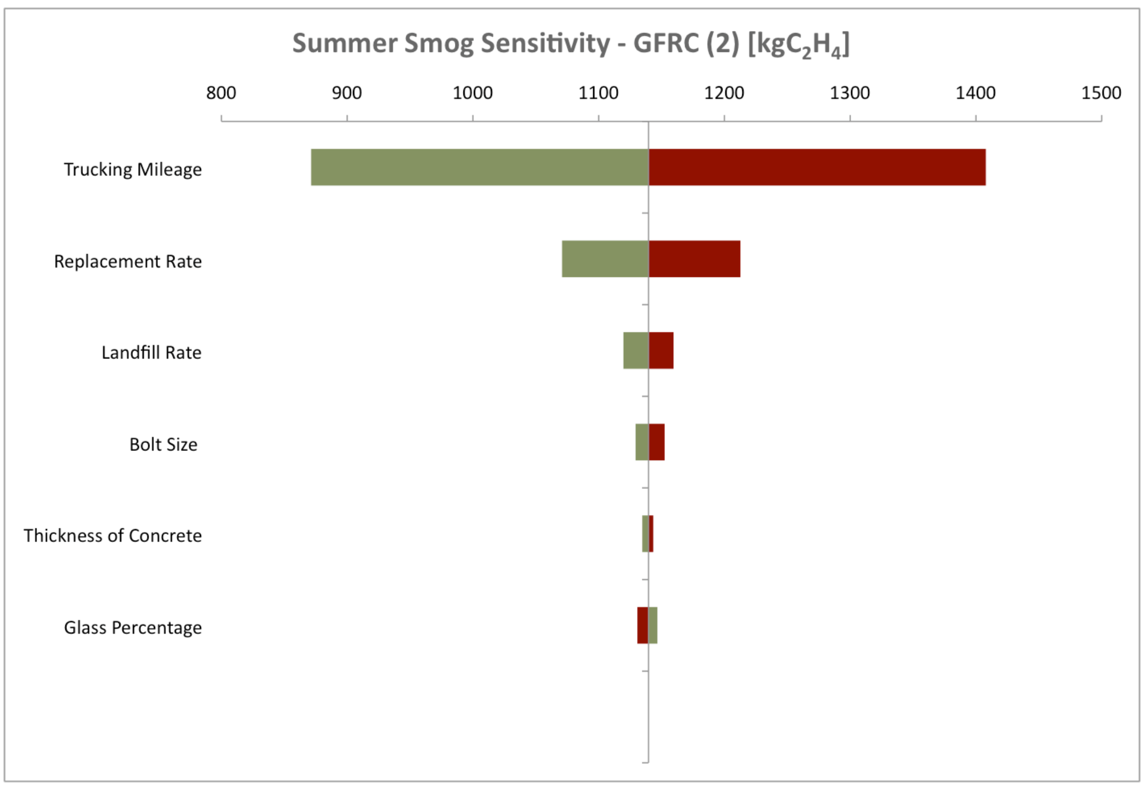

Carcinogens Sensitivity - FRP (2) [kg B(a)P]
0.04
0.042
0.044
0.046
0.048
0.05
0.052
0.054
0.056
0.058
Bolt Size
Trucking Mileage
Replacement Rate
Panel Thickness
Tape Usage
Alumina Trihydrate (Filler)
Pump Usage
Bag Usage

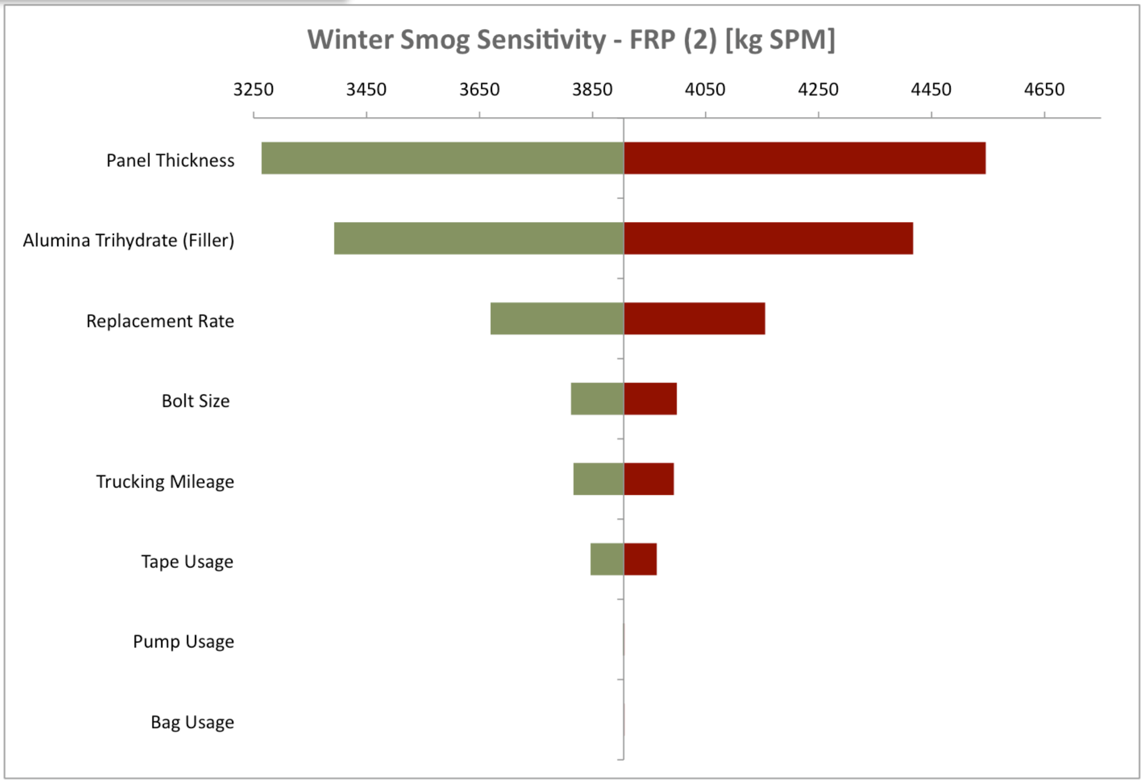

Carcinogens Sensitivity - GFRC (2) [kg B(a)P]
0.2
0.22
0.24
0.26
0.28
0.3
Trucking Mileage
Bolt Size
Replacement Rate
Thickness of Concrete
Glass Percentage
Landfill Rate

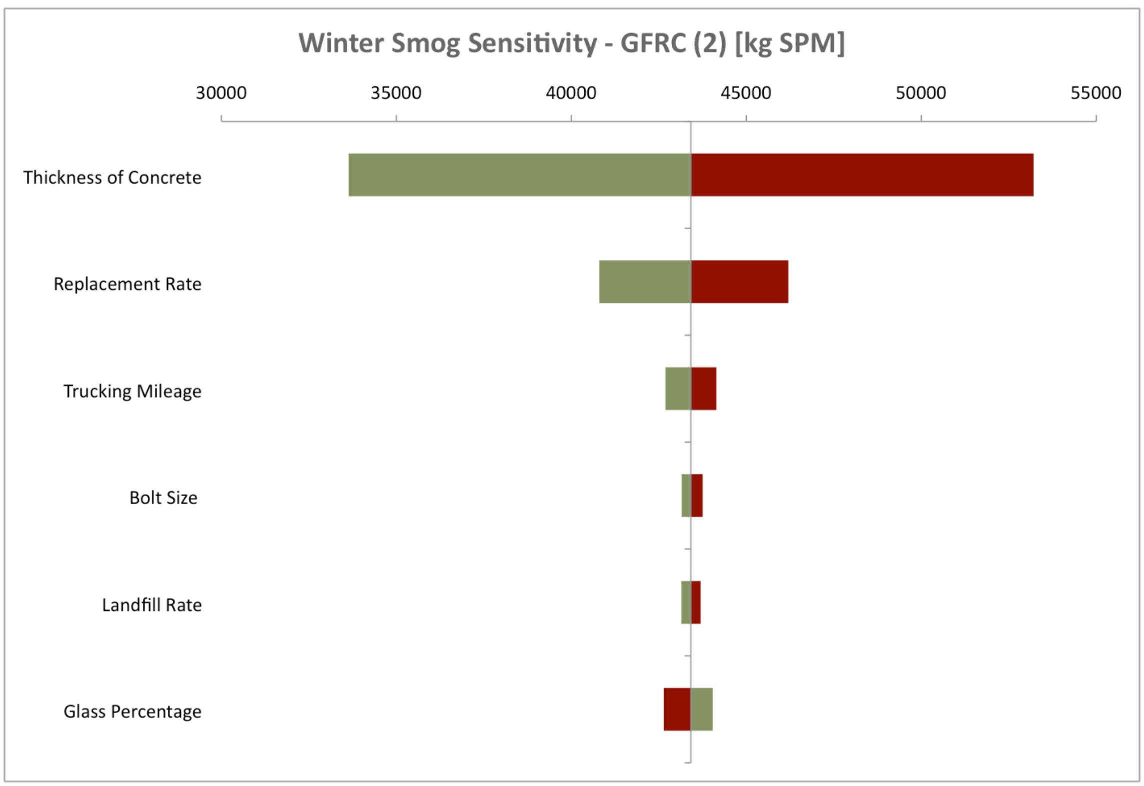

Summer Smog Sensitivity - FRP (2) [kg C_2H_4]
950
970
990
1010
1030
1050
1070
1090
Panel Thickness
Replacement Rate
Alumina Trihydrate (Filler)
Tape Usage
Trucking Mileage
Bolt Size
Pump Usage
Bag Usage

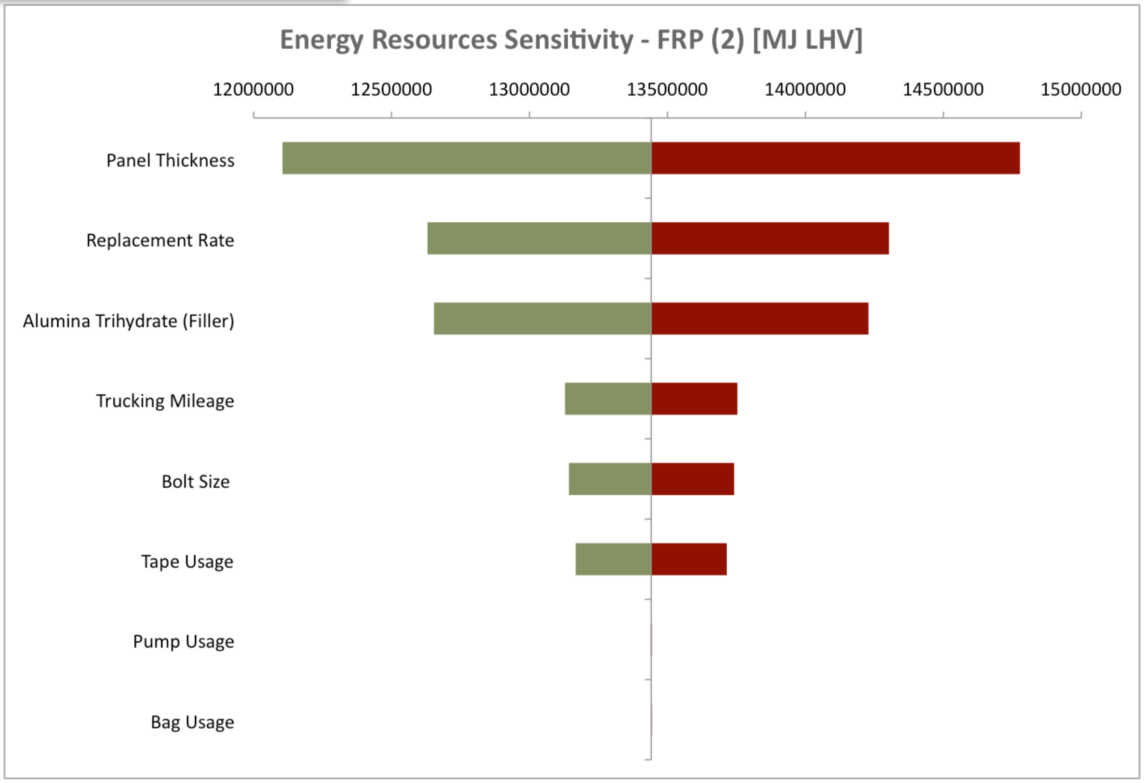

Summer Smog Sensitivity - GFRC (2) [kgC_2H_4]
800
900
1000
1100
1200
1300
1400
1500
Trucking Mileage
Replacement Rate
Landfill Rate
Bolt Size
Thickness of Concrete
Glass Percentage

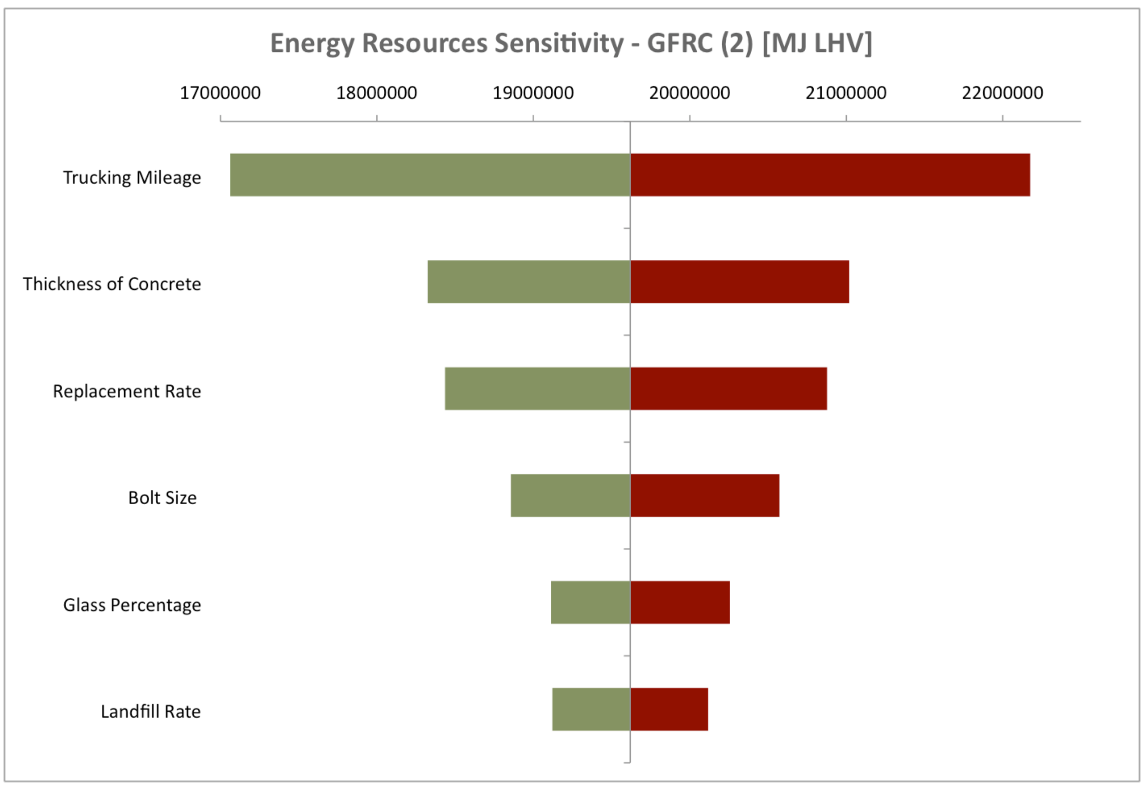

Winter Smog Sensitivity - FRP (2) [kg SPM]
3250
3450
3650
3850
4050
4250
4450
4650
Panel Thickness
Alumina Trihydrate (Filler)
Replacement Rate
Bolt Size
Trucking Mileage
Tape Usage
Pump Usage
Bag Usage

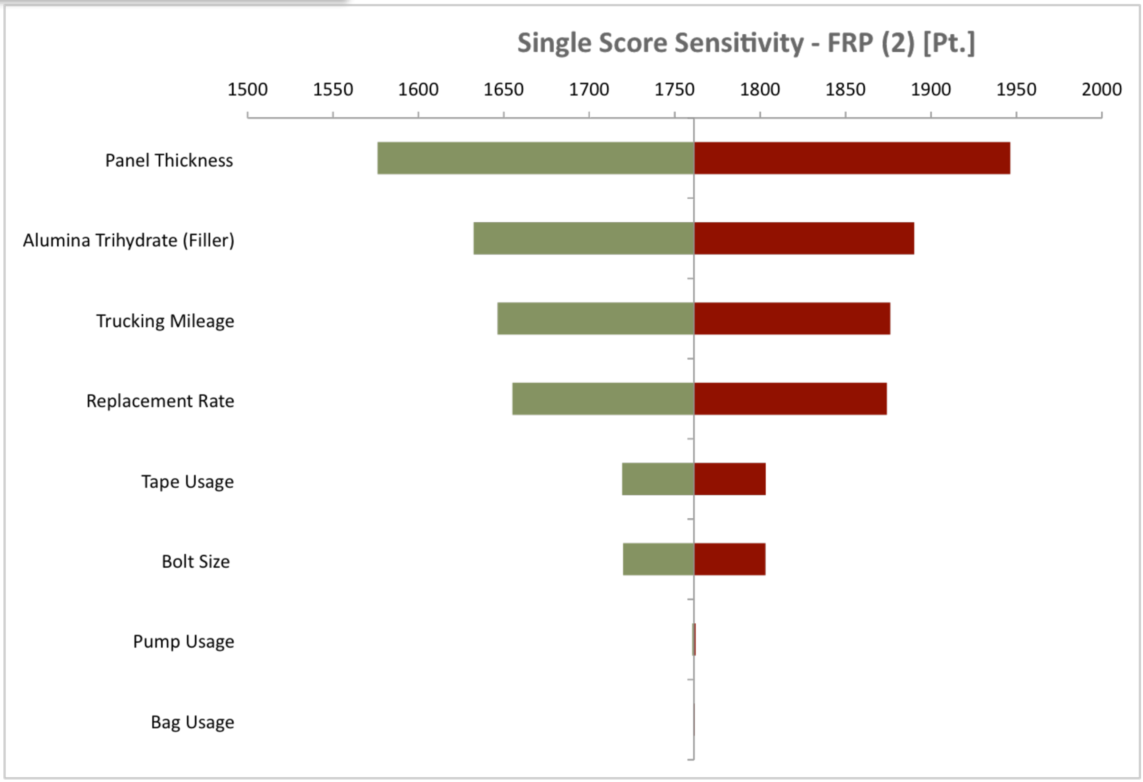

Summer Smog Sensitivity - GFRC (2) [kgC2H4]
800
900
1000
1100
1200
1300
1400
1500
Trucking Mileage
Replacement Rate
Landfill Rate
Bolt Size
Thickness of Concrete
Glass Percentage

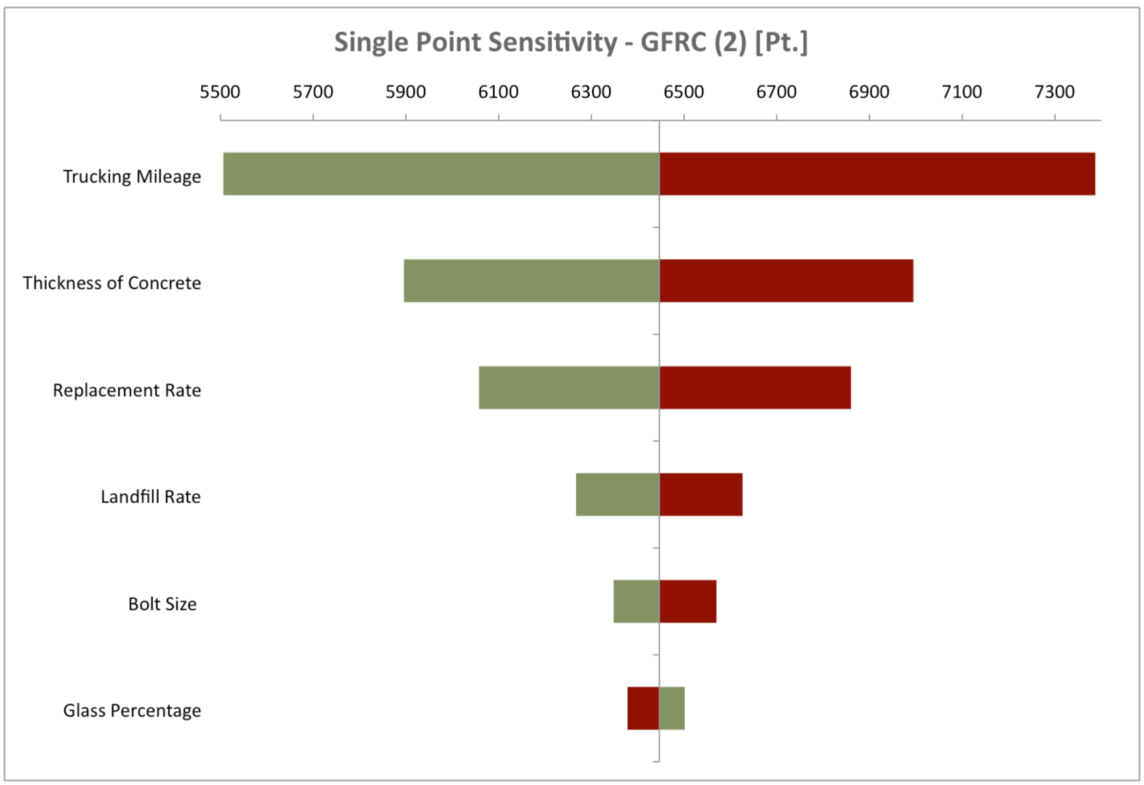

Winter Smog Sensitivity - FRP (2) [kg SPM]
3250
3450
3650
3850
4050
4250
4450
4650
Panel Thickness
Alumina Trihydrate (Filler)
Replacement Rate
Bolt Size
Trucking Mileage
Tape Usage
Pump Usage
Bag Usage


Winter Smog Sensitivity - GFRC (2) [kg SPM]
30000
35000
40000
45000
50000
55000
Thickness of Concrete
Replacement Rate
Trucking Mileage
Bolt Size
Landfill Rate
Glass Percentage


Energy Resources Sensitivity - FRP (2) [MJ LHV]
12000000
12500000
13000000
13500000
14000000
14500000
15000000
Panel Thickness
Replacement Rate
Alumina Trihydrate (Filler)
Trucking Mileage
Bolt Size
Tape Usage
Pump Usage
Bag Usage


Energy Resources Sensitivity - GFRC (2) [MJ LHV]
17000000
18000000
19000000
20000000
21000000
22000000
Trucking Mileage
Thickness of Concrete
Replacement Rate
Bolt Size
Glass Percentage
Landfill Rate


Single Score Sensitivity - FRP (2) [Pt.]
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
Panel Thickness
Alumina Trihydrate (Filler)
Trucking Mileage
Replacement Rate
Tape Usage
Bolt Size
Pump Usage
Bag Usage


Single Point Sensitivity - GFRC (2) [Pt.]
5500
5700
5900
6100
6300
6500
6700
6900
7100
7300
Trucking Mileage
Thickness of Concrete
Replacement Rate
Landfill Rate
Bolt Size
Glass Percentage

Appendix E: Life Cycle Cost Breakdown

	FRP	GFRC
Fabrication / Construction	$11.0 million	$13.0 million
Transportation	$ 260,000	$4.2 million
End of Life / Disposal	$1,000	$1,400
Total Cost	$11.2 million	$17.3 million
Cost per ft^2	$26.74 /$ft^2$	$41.03 /$ft^2$