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COMPARATIVE STUDY ON ENERGY PERFORMANCE OF DIFFERENT COMMERCIAL BUILDING WALL SYSTEMS

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ABSTRACT

Building sustainability has become one of the major interests of building owners and design professionals. To be more specific, there has been a consistent high demand on information of building energy performance. Wall systems, as an important part of a building, are therefore of interest. In order for design professionals to make better decision and select a wall system that can satisfy sustainable design objectives, they need to be better informed about each wall system available and suitable for the project. They also need to be able to compare the options with each other. This study is based upon previously conducted work that are relevant to the topic, and provides a comparison of some of the most commonly used wall systems of commercial buildings in terms of energy performance. The selected wall systems include curtain wall, brick veneer, and precast concrete panel with strip windows. The study was performed using Athena Impact Estimator for Buildings, a commercial LCA software for building analysis. Geographical location was also taken into account as a factor that affects embodied energy. The results obtained from computer software analysis were compared and presented in a comparative fashion. The results can be used to help select an optimal wall system for a commercial building project, in terms of sustainability features.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Chapter 1

Introduction

1.1 Background

With more people realizing the issues caused by global warming and increasing global energy consumption, considerations on sustainability have been valued greatly and put into various designs in the current world. One of such examples is building design. The current residential and commercial building energy consumption was calculated to be around 40 percent of total energy consumption in the US. Due to population growth and increased energy demand, this number has increased by about 25 percent for the past 35 years, and it has been predicted that the percentage will continue to grow to approximately 45 percent (U.S. Department of Energy, 2012). Therefore, great attention needs to be paid to effective measures that can reduce building energy consumption in order to improve the level of sustainability. This is particularly important to design professionals when they design new construction projects.

One of the main interests of design professionals when considering a building’s energy performance is the building wall system. There exist many different types of building wall systems, each with its own advantages and disadvantages in energy performance, structural behavior, aesthetics, etc. Therefore, a comparison is needed to aid design professionals make decisions when selection the most suitable wall system. Some studies have already been done on some commonly used residential building wall systems (Memari, et al., 2012; Memari, et al., 2014). Comparisons were made during these studies, and valuable conclusions were drawn in terms of energy and performance. However, there is not much readily available information of similar topics on commercial building wall systems. Since almost 50 percent of total building energy consumption comes from commercial buildings (U.S. Department of Energy, 2012), they deserve equal attention. A comparative study on energy performance of different commercial building wall systems is needed.

1.2 Objectives

This study was mainly to evaluate commonly utilized commercial building wall systems. For each system, the main focuses were on embodied energy and life cycle analysis. The results obtained from computer-aided analysis were to be compared among the chosen wall systems. From this, sustainable performance of each wall system could be better evaluated in a comparative fashion, which could help design professionals in selecting wall systems when designing commercial buildings.

1.3 Scope

This study exclusively focused on wall systems used in commercial building projects. To avoid unnecessary complexity of the study, only three very commonly used and currently popular wall systems were analyzed. The wall systems analyzed in this study include: glass curtain wall, masonry brick veneer, and precast concrete cladding panels with strip windows. In addition, despite there are many criteria for building sustainability, only embodied energy related aspects were investigated in this study.

1.4 Tasks

The tasks involved in this study are as follows:

- Review current literature on building sustainability and basic life cycle assessment (LCA) principles.
- Investigate recent studies on LCA of building systems, with attention to methods utilized.
- Overview information on the chosen commercial building wall systems.
- Analyze each wall system by using computer software.
- Compare and interpret the results obtained from the analysis.

Chapter 2

Literature Review

In this chapter, some key concepts and information will be discussed to help develop a better understanding on building sustainability, embodied energy, and life cycle assessment. Previously conducted studies and methodologies that are possible to be adopted for this study will also be investigated. In addition, some common commercial building wall systems will be identified to help further determine the scope of this study.

2.1 Embodied Energy and Life Cycle Assessment

Embodied energy is generally defined as the amount of energy required to produce one unit weight of a usable material (Ashby, 2013). Different materials are produced from different source: some require fossil fuels, while others consume electricity. In order to make embodied energy of different materials comparable, conventionally all energy sources are converted to oil equivalent (Ashby, 2013).

A life cycle assessment (LCA) is a study on a product's energy consumption, carbon emission, impact, etc. throughout its life cycle. For buildings, the main stages of life cycle are usually defined as material manufacturing, construction, use and maintenance, and end of life (Bayer, et al., 2010). As operational energy of a building during the use phase can be reduced by current building technologies, embodied energy during the materials manufacturing and construction phase becomes the primary part of an LCA (Bayer, et al., 2010).

Performing an LCA of a building is important when sustainability is of interest of the design professional. The results of such assessments can help design professionals gain more practical knowledge of the building materials so that better decisions can be made when selecting different materials and systems. This is particularly useful when the building project is attempting to obtain green building certification from common rating systems like Leadership in Energy and Environmental Design (LEED). In the most current version LEED v4, one major credit section is devoted for materials and resources, and worth more than 10 percent of the total points (U.S. Green Building Council, 2015).

Many methods have been developed in the industry to calculate the embodied energy in buildings. However, traditionally two methods have been considered the most popular and widely used: process analysis and input-output (I-O) analysis (Memari, et al., 2014). Process analysis would firstly require a bill of materials involved. Then, a material energy intensity database is utilized. The database contains values of energy per unit mass for various materials. The total embodied energy is simply computed by multiplying the energy intensity by the amount of material needed. However, one major drawback of this method is that numerous assumptions are usually necessary because of lack of information (Bayer, et al., 2010). The I-O analysis uses national energy data model of the economy. The database is divided into different sectors, each with a respective direct energy intensity and total energy intensity. It then needs to be determined which sector the material of interest belongs to estimate the embodied energy.

However, this method usually neglects some energy consumption during the production phase, which causes great inaccuracy for some materials (Bayer, et al., 2010). Therefore, in general, it is preferred to use modern analysis software that include more comprehensive data and produce more accurate results.

2.2 Recent Studies and Researches

There have been numerous LCA studies performed in the world in the past few years. Every study differs from each other in scope, objective, and methods, which greatly affect the quality of the results. Wallhagen et al. performed some basic LCA calculations on an office building in Sweden (Wallhagen, et al., 2011). The study was on a whole building scale, and each major component was evaluated in terms of embodied energy and CO_2 emission. Wu et al. conducted a similar study on an office building in China, and the scope of the study was also on the entire building (Wu, et al., 2012). Both embodied energy and carbon emission were analyzed, but the difference is the analysis was based on each phase of the building's life cycle instead of each system of the building. Kua et al. also had a whole-building LCA study on a multi-story commercial building in Singapore (Kua, et al., 2012). Similarly, each life cycle phase was investigated in terms of embodied energy and greenhouse gas emission. Many of these types of study focused on the scope of the whole building of interest, and all phases of the building's life cycle were analyzed. However, a full scale LCA is usually complex and time-consuming, and accurate results may not be obtainable (Ashby, 2013). In addition, these studies only looked at one single building of the authors' interest, and the objectives were not to provide a comparison of different building systems.

Johnson and Guggemos et al. conducted two comparative studies on building framing systems (Hsu, 2010). Both studies only focused on concrete and steel frames, and the buildings analyzed were proposed models instead of real buildings. Neither study was a full LCA. In addition to energy and CO_2, Guggemos et al. also assessed several other air pollutants (Hsu, 2010). Robertson et al. conducted a comparative LCA on timber and reinforced concrete used in mid-rise office building construction (Robertson, et al., 2012). Bribián et al. compared different building materials in terms of energy and environmental impact (Bribián, et al., 2011). Rossi et al. acknowledged the impact of location on LCA by investigating residential buildings in three locations in Europe (Rossi, et al., 2012). Cabeza et al. comprehensively reviewed several recent LCA's on buildings and evaluated several computer software commonly used in such tasks (Cabeza, et al., 2014). However, none of these studies really focused on the wall systems on the buildings.

Ottelé et al. studied and compared different green façade and living wall systems (Ottelé, et al., 2011). Stazi et al. assessed solar wall systems that can be used to improve building sustainability (Stazi, et al., 2012). However, these two studies were on newly emerged building envelope systems with sustainable attributes instead of currently widely used wall systems. Memari et al. performed a comparative LCA on several commonly used wall systems of residential buildings (Memari, et al., 2014). Both embodied energy and multi-hazard resistance were analyzed. Location factor was also taken into consideration. Kim compared a transparent composite façade system and a glass curtain wall system (Kim, 2011). However, the author acknowledged that climate and location were not considered in the study but could affect the performance of the systems. Limitations in life cycle assessment are understandable, however, due to the complex nature of LCA.

Therefore, although various LCA studies have been done in the building industry, there are not many comparative life cycle assessment studies on common commercial building wall systems.

2.3 Common Wall Systems of Commercial Buildings

Although there are many types of wall systems currently used in commercial building design, only the following three systems were analyzed in this study, given their commonness and popularity in the industry:

- Glass curtain wall
- Masonry brick veneer
- Precast concrete cladding panels with strip windows

A glass curtain wall is usually a thin aluminum-framed wall with glass in-fills. The framing is attached to the structural system, and does not carry any loads (Vigener, et al., 2012). A typical glass curtain wall is shown in Figure 2 (photo credit: Penn State University).

Figure 1 Typical Glass Curtain Wall Façade

Glass curtain wall can be further categorized into three system types. The first type is pressure-equalized rain screen system, which is considered as the most reliable type. It can block all forces that drive water across a barrier with the use of a pressure-equalization chamber that eliminates the pressure difference across the system. To achieve this, weep holes function as vents that allow air to flow between the exterior and glazing pocket. The second system is called water-managed system. It is similar to pressure-equalized system, but the difference is that there is no air barrier created. This would lead to the presence of high pressure difference between the glazing pocket and the interior, which causes water penetration and leaks. In this case, the weep holes would be used to drain out water that entered the system. The last and least common type is face-sealed barrier wall. It requires perfect seals at all member connections and does not perform ideally in long term (Vigener, et al., 2012).

To optimize thermal performance for glass curtain wall system, there are several issues that require close attention during the design process. The framing system usually uses aluminum, which is a material with high thermal conductivity. In order to reduce heat loss, the common practice is to provide thermal breaks that use material with low thermal conductivity. As for the opaque area of the wall, the lack of interior air layer can result in drastic changes in temperature and humidity under certain circumstances. Therefore, insulation and air/vapor barriers are often necessary in such areas. At the wall perimeter, insulation is also needed to prevent energy loss and possible condensation problems (Vigener, et al., 2012). In terms of sustainability, durability of the wall system is important. However, issues like condensation, dirt, thermal and structural deformation, exposure to water, environmental degradation can easily cause damage to the glazing and framing members (Vigener, et al., 2012). Incorporation of systems with well-designed thermal breaks and high R-values also improves the system's performance. In addition, the aluminum used in frames is conventionally recycled at the end of service life of the wall system (Vigener, et al., 2012).

The second common wall type of interest in this study is masonry brick veneer. It is a wall system made of exterior masonry units laid in mortar and functions as a cladding material. An interior wall, commonly steel framed wall, is needed to provide lateral support to the veneer (Weber, 2013). An example of masonry brick veneer is shown in Figure 3 (photo credit: Penn State University).

Figure 2 Typical Masonry Brick Veneer Façade

Water penetration can often occur in masonry wall systems. Spaces between masonry units and mortar can allow water to flow through. Water absorption of masonry units and mortar also contributes to water penetration in such wall systems (Weber, 2013). Therefore, several measure need to be taken to prevent potential damages caused by presence of moisture. Typically, drainage cavity should be placed behind the veneer to allow water to flow freely down to the base, from where water can be further redirected to the exterior of the wall. Moisture barrier is also required on the interior wall to prevent water from further penetration. Furthermore, condensation can potentially occur when air in the cavity contacts the fenestrations and other openings on the wall, which means cavity seals are generally required (Weber, 2013).

Masonry has very little insulating value, its temperature is easily affected by the surroundings. Therefore, insulation is needed in the drainage cavity or within the interior backup wall. However, in terms of safety, masonry walls are considerably superior to other wall systems, due to the materials inherent fire resistance. As for durability, masonry wall systems require minimum maintenance as compared to other systems, and has a typical service life of at least 100 years (Weber, 2013).

The third wall system used in this study is precast concrete cladding panels with strip windows. It is the most common use of precast concrete for building envelope systems. Like other types of building exterior wall systems, cladding panels do not bear any vertical loads; instead, they simply enclose the space within the building. The self-weight and lateral loads are transferred and supported by the main structural frames (Gaudette, 2009). These cladding panels are typically attached to the building at floor levels, and between each level of panels are strip windows. Figure 4 shows a typical wall system of this kind (photo credit: Penn State University).

Figure 3 Typical Precast Concrete Cladding Panel Façade with Strip Windows

Similar to masonry brick veneer wall system, the thermal performance of precast concrete cladding panel depends on the insulation installed in the drainage cavity or within the interior backup wall, which is generally steel stud wall. In terms of moisture protection, the common practices are uses of sealers or coatings to prevent water from penetrating the barrier. As for safety, precast concrete panels can cause serious damages when connections are compromised in case of fire. Durability and maintenance could be undesirable depending on the finishes and shapes of the cladding panels. Some finishes might result in vulnerability to water penetration, while others might lead to more likely deterioration of concrete or reinforcing steel. In addition, the relative complexity of installation can also cause damage and reduce durability. Improvement can be achieved by incorporating surface treatment and enhanced concrete mix (Gaudette, 2009).

Chapter 3

Modeling and Analysis

3.1 Plan of Study

In this comparative study on energy performance on different commercial building wall systems, three common used wall systems (glass curtain wall, masonry brick veneer, and precast concrete panels with strip windows) were selected. These three systems were further investigated by looking at components and materials involved in each system. The following step was to use Athena Impact Estimator for Buildings, a commercially available computer software, to analyze the three wall systems. In order to do this, a simple commercial building was modeled first. Then, by inputting the major components and materials of each wall system into the software, a life cycle assessment (LCA) was able to be conducted. To improve the value of the results, several locations in the US were chosen for this analysis because some parameters might vary in different locations. After the results became available, they were to be interpreted, graphed, and tabulated to facilitate the comparison among the three wall systems. From this, conclusions on sustainability and energy performance could be drawn to help determine which system has a relatively more satisfactory performance.

3.2 Building Modeling

The modeling and analysis of this building wall system study were performed using Athena Impact Estimator for Buildings. It is a commercial software that is developed to evaluate whole buildings and assemblies in accordance to internationally recognized LCA methodology. With the information in its database, the software is able to model 95% of the building stock in North America (Athena Sustainable Materials Institute, 2014). The software take into account of many life cycle stages ad factors that would affect the overall energy consumption of a building. These factors include material manufacturing, transportation, construction, region, building type and lifespan, maintenance and renovation, demolition and disposal (Athena Sustainable Materials Institute, 2014).

The building model represents a three-story commercial/office building. The building has a gross floor area of 45,000 square feet, with each floor having 15,000 square feet. The base dimension of the building is 150 feet × 100 feet. The total building height is 45 feet. The life expectancy of the building was estimated to be 60 years.

Athena Impact Estimator for Buildings also requires operating energy consumption data to construct the building model. More specifically, annual electricity and natural gas usage need to be provided. On average, office buildings in the US use approximately 17.3 kWh of electricity per square foot per year (Madison Gas and Electric, 2010). Therefore, for the modeled building, the total annual electricity usage is calculated as follows:

$$17.3\ \text{kWh/(ft}^2\text{•year)} \times 45{,}000\ \text{ft}^2 = 778{,}500\ \text{kWh/year}$$

The average natural gas consumption for office buildings in the US is about 31.8 cubic feet per square foot per year (Madison Gas and Electric, 2010). The total annual natural gas consumption for the building model is then calculated as follows:

$$31.8\ \text{ft}^3/(\text{ft}^2 \bullet \text{year}) \times 45{,}000\ \text{ft}^2 = 1{,}431{,}000\ \text{ft}^3/\text{year}$$

In this study, geographical location was also taken into consideration. This is because the location of a building affects energy consumption during transportation stage. In addition, the local climate also has an impact on the energy performance of a building. Therefore, five locations in the US, each with distinct climate, were selected: Pittsburgh PA, Orlando FL, Minneapolis MN, Seattle WA, and Los Angeles CA. Each building location was used to analyze the three commercial building wall systems of interest.

3.3 Wall Modeling

After a base building model was constructed in Athena Impact Estimator for Buildings, wall system was able to be modeled. Because the nature of this study is mainly comparison, it is not necessary to model all exterior walls of the building. Only one typical wall with dimensions of 150 feet × 45 feet was modeled for each wall system at each geographical location. Due to variations in construction of the three chosen wall systems, some assumptions were made to obtain typical exterior walls for the analysis.

For glass curtain walls, it was assumed that 80% of the exterior wall is viewable glazing and 20% is opaque glass spandrel panel at each floor level and roof level. Insulation with thickness of 2 inches was also included in the spandrel. The software uses default door dimensions of 32 inches × 7 feet. For the 150-foot-length of the wall, three sets of double doors, or six default doors in total, were used. The doors were assumed to be aluminum exterior door with 80% glazing, which has already been predefined in the software. Since the glazing already functions as windows, no additional windows needed to be specified in the model. This typical glass curtain wall system could be similarly represented in the detain drawing shown in Figure 4 (Morris, 2013).

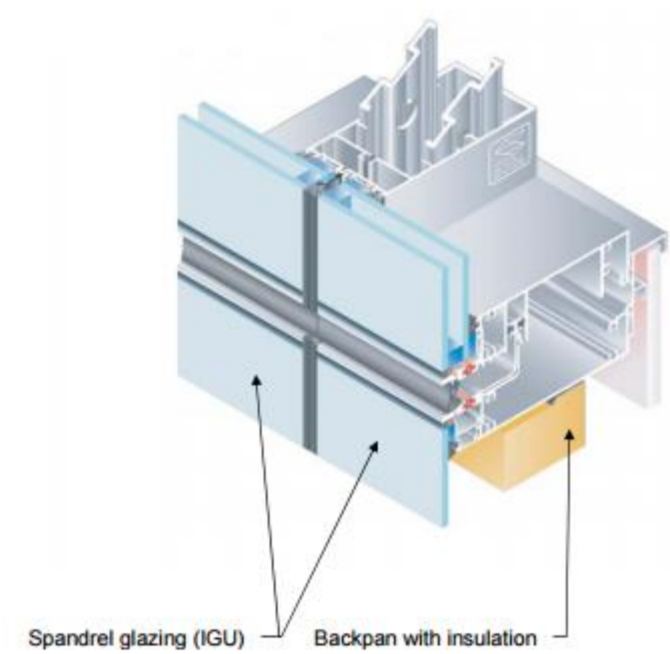

Figure 4 Typical Glass Curtain Wall Details

Brick veneer walls were assumed to be backed up by steel studs. The steel studs were chosen to be load bearing lightweight studs, with thickness of 6 inches and spacing of 16 inches o.c. The sheathing used for the wall is OSB. Standard bricks were used. The other envelope components involved in this wall system included ½-inch air barrier, ¼-inch polyethylene vapor barrier, 2-inch extruded polystyrene insulation, ½-inch gypsum board, and latex water based pain. It was assumed that there are 42 windows on the exterior wall, each with an area of 35 square feet. The windows are all double-panel with aluminum window frames, which is a predefined option in the software. Door openings were assumed the same as those on glass curtain wall models, in order to maintain consistency and eliminate effects of the doors. The typical masonry brick veneer wall details are similarly shown in Figure 5 (Lstiburek, 2015).

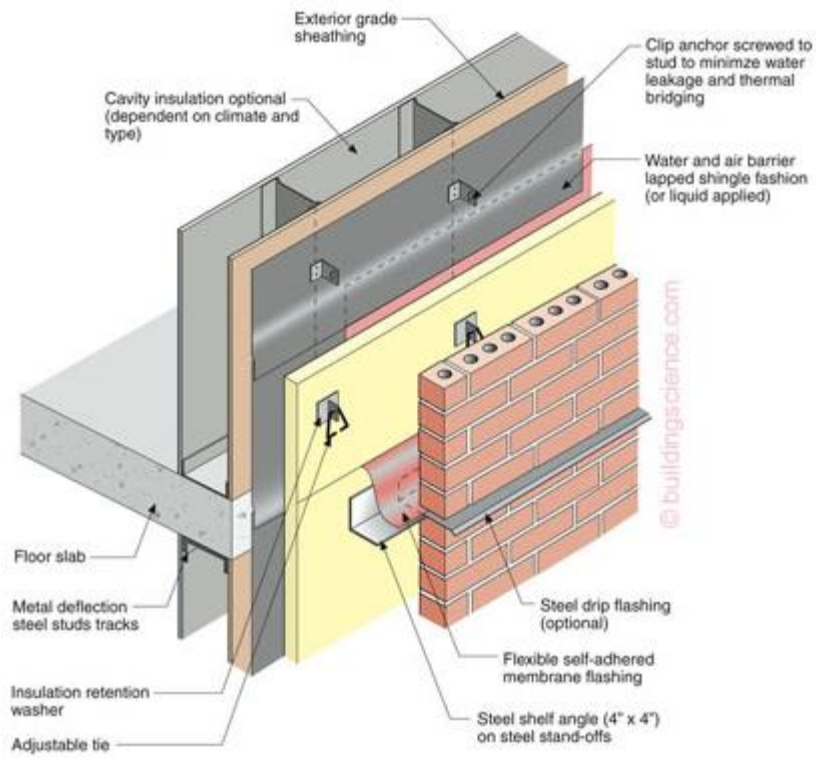

Figure 5 Typical Masonry Brick Veneer Details

Precast concrete panel walls also used steel studs, with the exact same setup and properties as in the brick veneer walls. Precast insulated panels were used for this type of wall system. The other envelope components and doors were assumed the same as in the brick veneer models. This would maintain consistency of the models and eliminate effects on energy performance from minor components in the wall systems. The windows in this wall system are strip windows. It was assumed that there are totally 75 window panels that make up the strip windows on the three floors, each window still with an area of 35 square feet. A detail drawing of a similar typical precast concrete cladding panel wall is shown in Figure 6 (Straube, 2012).

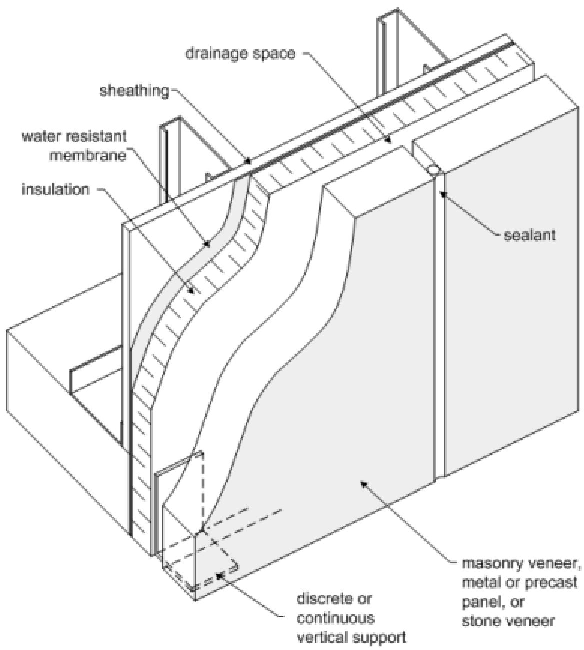

Figure 6 Typical Precast Concrete Cladding Panel Details

After modeling the base building and the typical walls, Athena Impact Estimator for Buildings was able to analyze the components and materials involved, and produce results regarding energy and fossil fuel consumptions. The results could be further evaluated based on data in the output files the software generated.

Chapter 4

Results and Discussions

4.1 Comparison of Wall Systems

Fifteen wall models, three wall systems in five locations, were made for the base building model in Athena Impact Estimator for buildings. The software includes operational energy use in the use phase of a building assembly's life cycle. This energy was found to be significant more intensive than any other category of energy use. Since it mainly depends on the annual electricity and natural gas consumptions and national average values were input into the models, operational energy use would not contribute to the comparisons made to evaluate each specific wall system in different locations. Therefore, in the analysis for this study, all operational energy uses were not taken into consideration. Athena Impact Estimator for Buildings also provides primary energy data for Beyond Building Life phase, which is the energy credit a system can receive after being recycled or reused. However, in this relatively simplified LCA study, this phase is not of particular interest, and therefore, neglected. The results were graphed and are shown in Figure 7-12. Note that Figure 12 represents the average values of data in all five geographical locations.

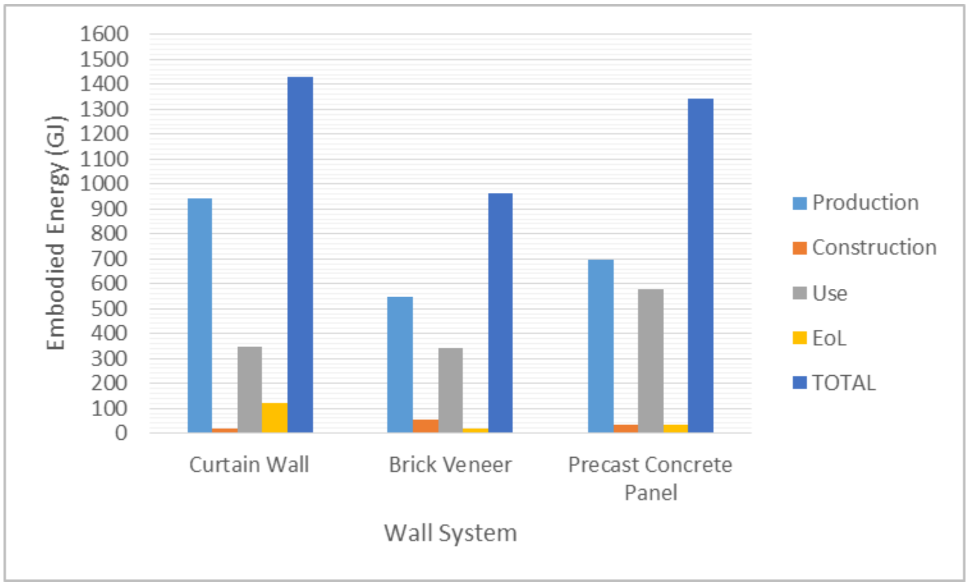

Figure 7 Embodied Energy of Wall Systems (Pittsburgh, PA)

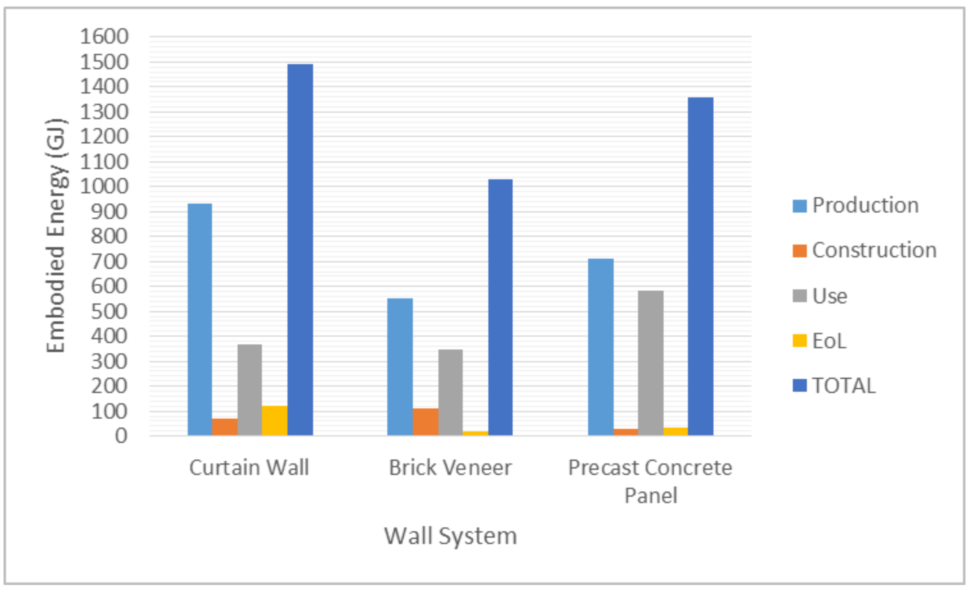

Figure 8 Embodied Energy of Wall Systems (Orlando, FL)

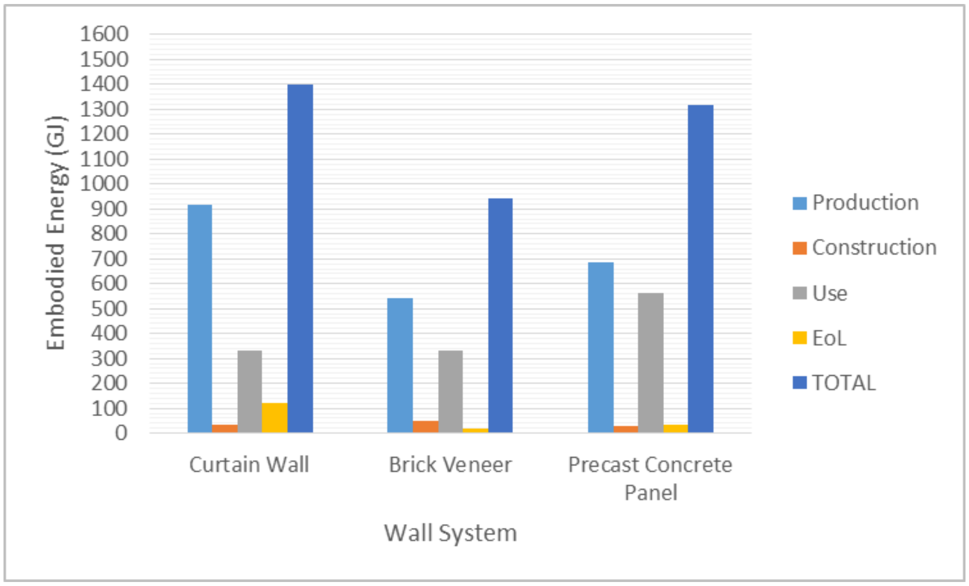

Figure 9 Embodied Energy of Wall Systems (Minneapolis, MN)

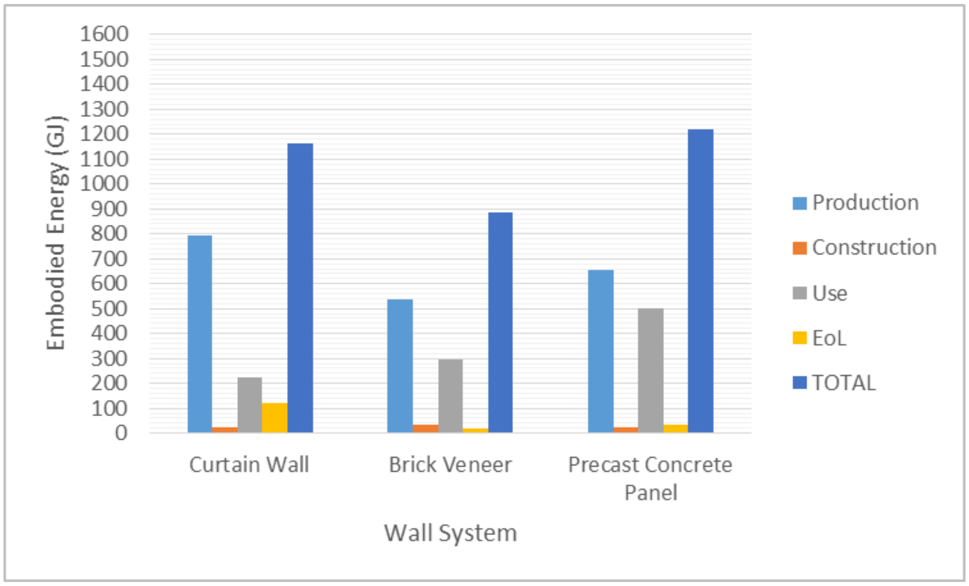

Figure 10 Embodied Energy of Wall Systems (Seattle, WA)

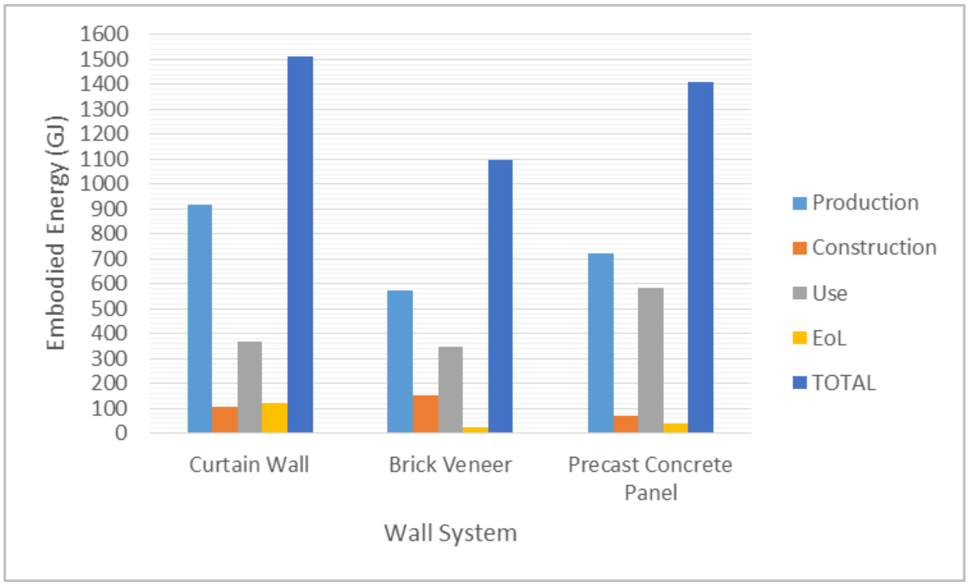

Figure 11 Embodied Energy of Wall Systems (Los Angeles, CA)

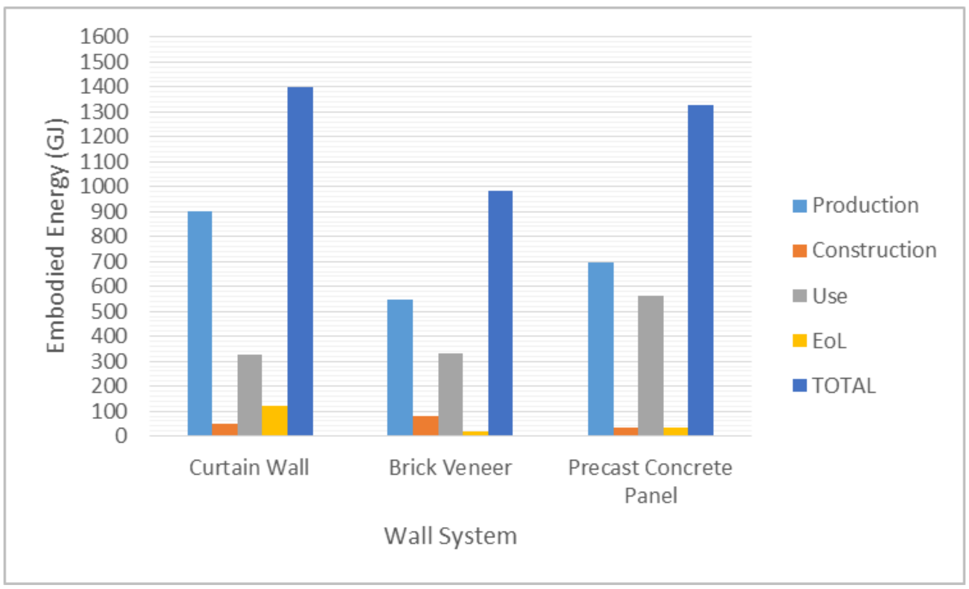

Figure 12 Embodied Energy of Wall Systems (Average)

The results are obvious in that for all three wall systems, production phase and use phase are significantly more energy intensive than construction phase and End of Life (EoL) phase. This was expected because manufacturing of the materials and maintenance of the systems both require a large amount of energy.

It was found that in general, glass curtain wall system has the most total embodied energy, and brick veneer wall system has the least. On average, the total primary energy of curtain wall is about 1400 GJ, brick veneer is 983 GJ, and precast concrete panel (PCP) is 1328 GJ. Additionally, the total embodied energy is dominated by energy used in production phase, which is the main energy consumption phase for all wall types. Curtain wall has the most total embodied energy because it has the most embodied energy during production and manufacturing. This trend shows that glass manufacturing consumes more energy than that of other materials. Precast concrete cladding panel walls use about 26% more energy than brick veneer walls during production phase. This is partially due to the use of strip windows in PCP wall systems, which almost doubled the amount of windows brick veneer wall has. However, the quantity and gross area of the windows were based on estimations for this specific study. If assumptions for windows were changed, the results would somewhat be affected. Another reason PCP consumes more energy in production than brick veneer is that cementitious materials like concrete require massive energy input to extract raw materials from the earth and process materials in high-temperature kilns (Memari, et al., 2014). Conventional clay brick production, however, does not involve such energy intensive processes.

As for use and maintenance, the second major energy consumption phase, PCP has the most embodied energy. On average, it is approximately 70% more than the other two wall systems. The reason PCP requires so much energy during use phase is that PCP is very vulnerable to damages. Its resilience and durability are not desirable, and maintenance can be very energy intensive and costly. Brick veneer, on the other hand, consumes much less energy in use phase. Only minimum maintenance is needed because of the material's satisfactory durability. Glass curtain wall, in general, has about the same amount of embodied energy for use and maintenance as brick veneer wall.

For construction phase, it was discovered that brick veneer wall uses the most energy among the three wall types. This might be due to the fact that brick veneer is sometimes not used in a panelized fashion in construction, which results in higher difficulty of construction and more uses of equipment that are energy intensive. Despite the complexity in construction for both curtain wall and precast concrete panel wall, they require much less energy than brick veneer.

In terms of End of Life phase, glass curtain seems to consume significantly more energy than the other two walls. This is because at the end of a curtain wall's life cycle, the glass glazing and aluminum framing are usually recycled, and the processing methods can require a large amount of energy. PCP can be recycled as well after service life, but the reprocessing is not as energy intensive as that of a glass curtain wall. The complexity in construction of PCP also means complexity in demolition, which increase energy usage in this phase (Memari, et al., 2014). However, overall the embodied energy PCP has during EoL phase is still much less than that of curtain wall. In addition, it was found that brick veneer has the lowest embodied energy in this phase of a life cycle. This is because after its service life, brick veneer can be easily demolished and disposed to landfill or recycled. Usually, these processes are not very energy intensive, which lowers the embodied energy during EoL phase.

4.2 Comparison of Geographical Locations

Geographical locations were taken into consideration of this LCA study, because embodied energy varies for different locations even if the buildings are identical. Material availability, construction methods, transportation, etc. will have an impact on a building's embodied energy (Memari, et al., 2014). By analyzing the same three wall systems in five different geographical locations in the US, the results can be more representative, comprehensive, and applicable to building projects in various areas in the US. Therefore, the output data from Athena Impact Estimator for Buildings were re-graphed based on geographical locations instead of wall systems. They are represented in Figure 13-15.

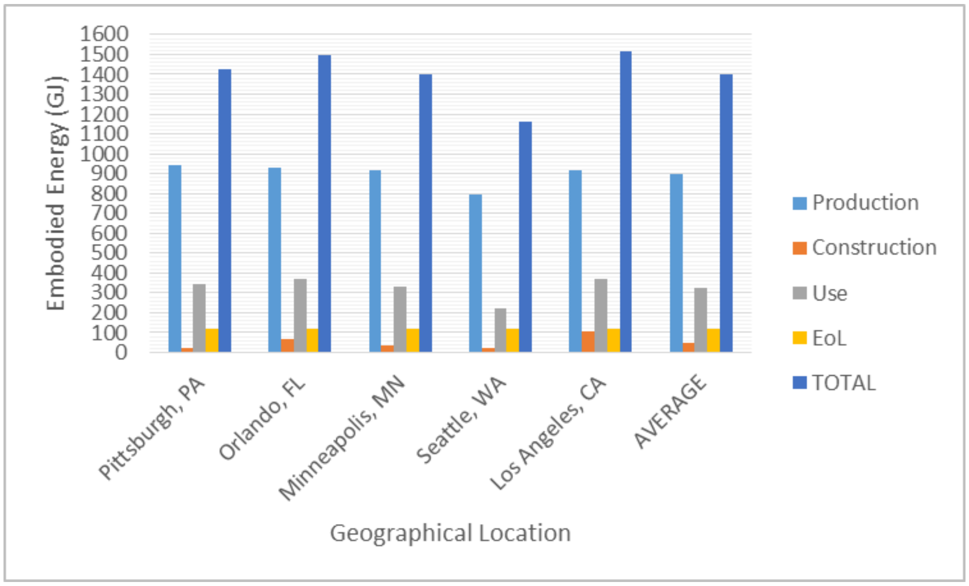

Figure 13 Embodied Energy of Wall Systems (Curtain Wall)

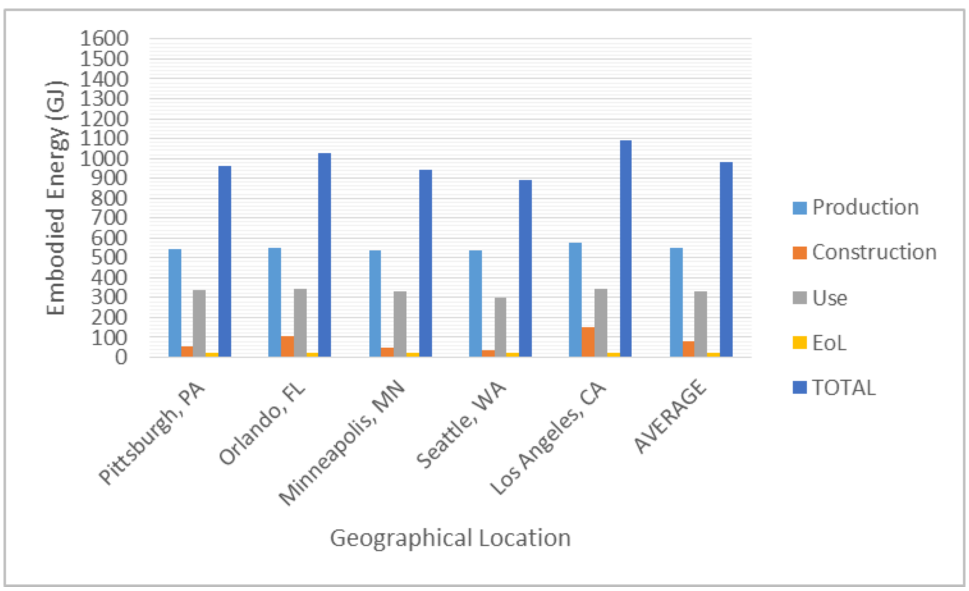

Figure 14 Embodied Energy of Wall Systems (Brick Veneer)

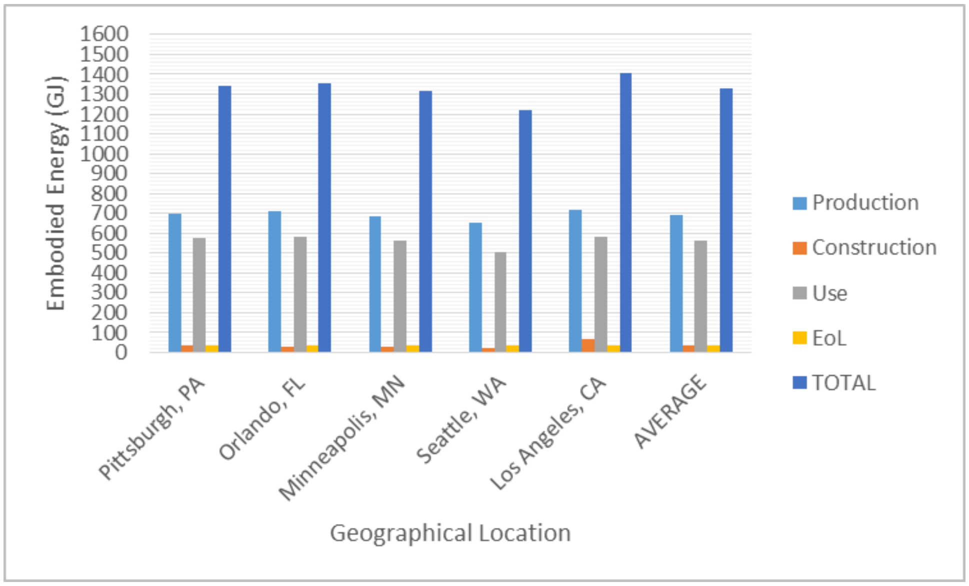

Figure 15 Embodied Energy of Wall Systems (Precast Concrete Panel)

From the figures, it can be observed that Los Angeles has the highest embodied energy for all three wall systems, followed by Orlando, Pittsburgh, Minneapolis, then Seattle, which has the lowest embodied energy among all five geographical locations. In comparison, Los Angeles leads Seattle by 15%-30%, depending on wall type. In terms of production and manufacturing energy, most cities have very similar energy consumption level, except Seattle, which has lower. This might be due to Seattle has more widely available materials and easy transportation to sites.

As for use and maintenance energy, Los Angeles and Orlando seem to consumer the most, followed by Pittsburgh and Minneapolis. Once again, Seattle uses the lowest embodied energy in this phase of a life cycle. In relatively hot climate regions like Los Angeles and Orlando, building components are subject to more thermal, moisture, and wind damages than the other locations. Therefore, it is reasonable that the two locations cause high energy consumption during the use and maintenance phase. Pittsburgh and Minneapolis are affected by natural damages caused by cold climates, so the energy consumption level is also relatively high in such regions. However, Seattle has a relatively very mild climate, which reduces potential natural damages.

Los Angeles also has the highest construction energy consumption among the five locations. This is because when compared to other locations, Los Angeles is relatively more difficult to access from building material manufacturing facilities. The long distance and the city's scale cause transportation energy use during construction phase to rise. In addition, EoL energy is approximately the same for all five locations. The reason of this is that the demolition and recycling methods of the same wall system are similar in all geographical locations.

4.3 Ranking and Summary

The modeling results from Athena Impact Estimator for Buildings are tabulated and represented in Table 1 and Table 2, with exact values shown. Table 1 provides data for embodied energy of the three wall systems in five geographical locations, and Table 2 shows data for carbon emission of each wall system in each life cycle phase. The standard measurement of global warming potential is in kg CO_2 equivalent, which means all relevant factors are converted into carbon dioxide. This parameter, in addition to embodied energy, is also often of interest when performing life cycle assessment.

Table 1 Embodied Energy Summary

Embodied Energy Summary (GJ)					
Pittsburgh, PA					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	942	20	345	122	1428
Brick Veneer	545	56	341	20	962
Precast Concrete Panel	697	33	577	36	1343
Orlando, FL					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	933	69	370	122	1494
Brick Veneer	553	109	346	20	1028
Precast Concrete Panel	710	27	584	36	1357
Minneapolis, MN					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	916	33	330	122	1400
Brick Veneer	540	48	333	20	941
Precast Concrete Panel	687	30	563	36	1316
Seattle, WA					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	793	22	225	122	1161
Brick Veneer	536	35	297	20	888
Precast Concrete Panel	656	24	502	36	1219
Los Angeles, CA					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	917	107	369	122	1515
Brick Veneer	574	153	346	21	1094
Precast Concrete Panel	720	68	583	37	1408
AVERAGE					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	900	50	327	122	1400
Brick Veneer	550	80	333	20	983
Precast Concrete Panel	694	36	562	36	1328

Table 2 Carbon Emission Summary

Carbon Emission Summary (10^3 kg CO_2 eq.)					
Pittsburgh, PA					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	105	1.5	46	9.5	162
Brick Veneer	37	4.0	28	1.5	71
Precast Concrete Panel	61	2.3	49	2.6	115
Orlando, FL					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	104	5.2	47	9.5	166
Brick Veneer	38	8.0	29	1.6	76
Precast Concrete Panel	62	1.9	49	2.6	115
Minneapolis, MN					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	102	2.5	44	9.5	158
Brick Veneer	37	3.5	28	1.5	70
Precast Concrete Panel	61	2.1	48	2.6	113
Seattle, WA					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	93	1.4	37	9.5	141
Brick Veneer	36	2.3	25	1.6	65
Precast Concrete Panel	57	1.5	43	2.6	105
Los Angeles, CA					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	102	7.9	47	9.5	166
Brick Veneer	38	10	29	1.6	79
Precast Concrete Panel	62	4.8	49	2.7	118
AVERAGE					
	Production	Construction	Use	End of Life	TOTAL
Curtain Wall	101	3.7	44	9.5	159
Brick Veneer	37	5.6	28	1.6	72
Precast Concrete Panel	60	2.5	48	2.6	113

From the tables, it can be seen that for both embodied energy and carbon emission, brick veneer generally has the best performance, followed by precast concrete panel and then curtain wall, which has the least satisfactory performance. Furthermore, location indeed has an impact on energy and carbon performance, although the differences are relatively small. In order to compare the obtained results in a more straightforward manner, a comprehensive ranking system was developed and is shown in Table 3.

Table 3 Common Commercial Building Wall System Ranking

Common Commercial Building Wall System Ranking						
	Embodied Energy					
Wall Type	Pittsburgh, PA	Orlando, FL	Minneapolis, MN	Seattle, WA	Los Angeles, CA	AVERAGE
Curtain Wall	III	III-	III	II	III-	III
Brick Veneer	I-	II+	I	I	II	I-
Precast Concrete Panel	III	III	III	II-	III	III
	Carbon Emission					
Wall Type	Pittsburgh, PA	Orlando, FL	Minneapolis, MN	Seattle, WA	Los Angeles, CA	AVERAGE
Curtain Wall	3	3	3+	2-	3	3+
Brick Veneer	1	1	1	1	1	1
Precast Concrete Panel	2	2	2	2+	2	2
Note:	I+ & 1+ = Best	III- & 3- = Worst				

The ranking matrix developed provides a simpler presentation that can be used to compare and evaluate the embodied energy and carbon emission of the three selected common commercial building wall types. However, this simple matrix is only based on the output data from Athena Impact Estimator for Buildings, with many assumptions made. In order for the ranking matrix to better assist design professionals in the selection process of a sustainable wall system, more criteria and data need to be incorporated.

Chapter 5

Conclusions

From literature review and analysis of modeling results in this life cycle assessment study on common commercial building wall systems, several conclusions can be drawn. For all building exterior wall systems, the production phase and use phase of a life cycle are the major stages in which energy is consumed. In order to improve energy performance of a wall system, more energy efficient manufacturing and maintenance methods need to be implemented. Production energy is greatly affected by the use of windows and glazing systems. The more glass utilized, the higher level of energy consumption a wall system has. Durability of the materials directly affects the need of maintenance. Less resilient wall systems will use more energy during use phase. Construction energy usage correlates to the complexity of construction, and End of Life energy is related to the methods of recycling, reusing, and disposal. Overall, curtain wall consumes the most energy and has the most carbon footprint, brick veneer is more ideal in terms of energy and carbon performance.

Geographical location was also proved to have effects on embodied energy and carbon emission. In regions where temperature and moisture content are high or cold climate exists, exterior wall systems are much easier to be damaged which increase energy consumption during use and maintenance phase. Some regions are also greatly affected by availability of material and easiness of transportation, since transportation requires large amounts of fossil fuels and emits greenhouse gases that contribute to global warming.

Therefore, when evaluate the sustainability features of a commercial building exterior wall system, one must consider all the relevant factors to make more accurate ad reasonable decisions. However, sustainability features like embodied energy and carbon emission should not be the only criteria when selection the most applicable wall type. Design professional should also considered many other important factors like owner requirements, safety, economical design, wind and seismic resistance, thermal performance, moisture response, indoor environment, occupant health, aesthetics, etc. In order to select the optimal exterior wall system, all applicable criteria need to be carefully evaluated.

For future studies and researches, one can focus on considering more commonly used exterior wall systems for commercial buildings. Height of the building may also affect wall type selection, as certain wall types are not applicable to high-rise buildings. Other more advanced software can be used to obtain better models. More realistic assumptions can also be made to improve the quality of the result data. In addition, other criteria that affect a building exterior wall system should be reasonably included as well.

Appendix A

Athena Impact Estimator for Buildings Data

Table A1 Bill of Materials Report (Curtain Wall, Pittsburgh, PA)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
Aluminum Extrusion	Tons (short)	8.7197	0	0	0	0	8.7197	0	8.7197	Tons (short)
EPDM membrane (black, 60 mil)	lbs	707.5478	0	0	0	0	707.5478	0	0.3538	Tons (short)
FG Batt R11-15	sf (1")	5571.7488	0	0	0	0	5571.749	0	0.1786	Tons (short)
Glazing Panel	Tons (short)	40.7161	0	0	0	0	40.7161	0	40.7161	Tons (short)
Nails	Tons (short)	0.0259	0	0	0	0	0.0259	0	0.0259	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.2941	0	0	0	0	0.2941	0	0.2941	Tons (short)
Spandrel Panel	Tons (short)	1.0936	0	0	0	0	1.0936	0	1.0936	Tons (short)

Table A2 Detailed Summary Measure Table By Life Cycle Stages (Curtain Wall, Pittsburgh, PA)

		PRODUCT (A1 to A3)			CONSTRUCTION PROCESS (A4 & A5)			USE (B2, B4 & B6)			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	1.05E+05	5.16E+02	**1.05E+05**	8.28E+02	6.87E+02	**1.52E+03**	4.53E+04	9.54E+02	3.46E+07	**3.47E+07**
Acidification Potential	kg SO2 eq	6.25E+02	5.09E+00	**6.30E+02**	6.01E+00	7.23E+00	**1.32E+01**	2.84E+02	9.50E+00	2.95E+05	**2.95E+05**
HH Particulate	kg PM2.5 eq	8.79E+02	2.86E-01	**8.79E+02**	4.36E-01	3.93E-01	**8.29E-01**	7.00E+02	5.33E-01	3.04E+04	**3.11E+04**
Eutrophication Potential	kg N eq	2.03E+01	3.46E-01	**2.07E+01**	2.46E-01	4.89E-01	**7.35E-01**	1.20E+01	6.45E-01	3.54E+03	**3.55E+03**
Ozone Depletion Potential	kg CFC-11 eq	5.50E-05	1.98E-08	**5.50E-05**	6.14E-07	2.82E-08	**6.42E-07**	3.39E-05	3.72E-08	1.85E-05	**5.24E-05**
Smog Potential	kg O3 eq	8.68E+03	1.77E+02	**8.85E+03**	1.19E+02	2.52E+02	**3.70E+02**	5.15E+03	3.31E+02	1.62E+06	**1.63E+06**
Total Primary Energy	MJ	9.35E+05	6.98E+03	**9.42E+05**	1.04E+04	9.36E+03	**1.97E+04**	3.32E+05	1.27E+04	5.86E+08	**5.86E+08**
Non-Renewable Energy	MJ	9.23E+05	6.97E+03	**9.30E+05**	1.03E+04	9.36E+03	**1.97E+04**	3.27E+05	1.27E+04	5.81E+08	**5.81E+08**
Fossil Fuel Consumption	MJ	8.59E+05	6.96E+03	**8.66E+05**	9.91E+03	9.34E+03	**1.93E+04**	2.92E+05	1.27E+04	4.66E+08	**4.66E+08**

END OF LIFE (C1 to C4)			BEYOND BUILDING LIFE (D)			TOTAL EFFECTS	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
9.28E+03	2.14E+02	**9.49E+03**	-5.12E+03	0.00E+00	**-5.12E+03**	**3.48E+07**	**3.48E+07**
4.39E+01	1.93E+00	**4.58E+01**	-2.36E+01	0.00E+00	**-2.36E+01**	**2.96E+05**	**2.96E+05**
3.63E+00	1.16E-01	**3.75E+00**	-1.92E+00	0.00E+00	**-1.92E+00**	**3.20E+04**	**3.20E+04**

1.11E+00	1.32E-01	**1.24E+00**	-5.32E-01	0.00E+00	**-5.32E-01**	**3.57E+03**	**3.57E+03**
8.81E-07	7.67E-09	**8.89E-07**	-5.05E-07	0.00E+00	**-5.05E-07**	**1.09E-04**	**1.08E-04**
4.76E+02	6.70E+01	**5.43E+02**	-2.21E+02	0.00E+00	**-2.21E+02**	**1.64E+06**	**1.64E+06**
1.19E+05	2.61E+03	**1.22E+05**	-6.67E+04	0.00E+00	**-6.67E+04**	**5.87E+08**	**5.87E+08**
1.18E+05	2.61E+03	**1.21E+05**	-6.60E+04	0.00E+00	**-6.60E+04**	**5.82E+08**	**5.82E+08**
1.13E+05	2.60E+03	**1.16E+05**	-6.24E+04	0.00E+00	**-6.24E+04**	**4.67E+08**	**4.67E+08**

Table A3 Bill of Materials Report (Curtain Wall, Orlando, FL)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
Aluminum Extrusion	Tons (short)	8.7197	0	0	0	0	8.7197	0	8.7197	Tons (short)
EPDM membrane (black, 60 mil)	lbs	707.5478	0	0	0	0	707.5478	0	0.3538	Tons (short)
FG Batt R11-15	sf (1")	5571.7488	0	0	0	0	5571.749	0	0.1786	Tons (short)
Glazing Panel	Tons (short)	40.7161	0	0	0	0	40.7161	0	40.7161	Tons (short)
Nails	Tons (short)	0.0259	0	0	0	0	0.0259	0	0.0259	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.2941	0	0	0	0	0.2941	0	0.2941	Tons (short)
Spandrel Panel	Tons (short)	1.0936	0	0	0	0	1.0936	0	1.0936	Tons (short)

Table A4 Detailed Summary Measure Table By Life Cycle Stages (Curtain Wall, Orlando, FL)

		PRODUCT (A1 to A3)			CONSTRUCTION PROCESS (A4 & A5)			USE (B2, B4 & B6)			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	1.03E+05	5.14E+02	**1.04E+05**	8.29E+02	4.32E+03	**5.15E+03**	4.41E+04	3.37E+03	3.96E+07	**3.97E+07**
Acidification Potential	kg SO2 eq	6.06E+02	5.07E+00	**6.11E+02**	6.00E+00	4.55E+01	**5.15E+01**	2.69E+02	3.49E+01	3.28E+05	**3.28E+05**
HH Particulate	kg PM2.5 eq	8.76E+02	2.85E-01	**8.77E+02**	4.34E-01	2.47E+00	**2.91E+00**	6.97E+02	1.91E+00	2.65E+04	**2.72E+04**
Eutrophication Potential	kg N eq	1.98E+01	3.44E-01	**2.01E+01**	2.45E-01	3.08E+00	**3.32E+00**	1.16E+01	2.36E+00	3.50E+03	**3.51E+03**
Ozone Depletion Potential	kg CFC-11 eq	5.50E-05	1.98E-08	**5.50E-05**	6.14E-07	1.77E-07	**7.92E-07**	3.39E-05	1.36E-07	4.38E-05	**7.78E-05**
Smog Potential	kg O3 eq	8.33E+03	1.76E+02	**8.51E+03**	1.18E+02	1.58E+03	**1.70E+03**	4.87E+03	1.21E+03	1.25E+06	**1.25E+06**
Total Primary Energy	MJ	9.26E+05	6.93E+03	**9.33E+05**	1.04E+04	5.89E+04	**6.93E+04**	3.24E+05	4.56E+04	6.57E+08	**6.57E+08**
Non-Renewable Energy	MJ	9.07E+05	6.93E+03	**9.14E+05**	1.03E+04	5.89E+04	**6.92E+04**	3.14E+05	4.55E+04	6.51E+08	**6.52E+08**
Fossil Fuel Consumption	MJ	8.50E+05	6.91E+03	**8.57E+05**	9.95E+03	5.88E+04	**6.87E+04**	2.85E+05	4.55E+04	6.19E+08	**6.19E+08**

END OF LIFE (C1 to C4)			BEYOND BUILDING LIFE (D)			TOTAL EFFECTS	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
9.28E+03	2.14E+02	**9.49E+03**	-5.12E+03	0.00E+00	**-5.12E+03**	**3.98E+07**	**3.98E+07**
4.39E+01	1.93E+00	**4.58E+01**	-2.36E+01	0.00E+00	**-2.36E+01**	**3.29E+05**	**3.29E+05**
3.63E+00	1.16E-01	**3.74E+00**	-1.92E+00	0.00E+00	**-1.92E+00**	**2.81E+04**	**2.81E+04**

1.11E+00	1.32E-01	**1.24E+00**	-5.32E-01	0.00E+00	**-5.32E-01**	**3.53E+03**	**3.53E+03**
8.81E-07	7.67E-09	**8.89E-07**	-5.05E-07	0.00E+00	**-5.05E-07**	**1.34E-04**	**1.34E-04**
4.76E+02	6.70E+01	**5.43E+02**	-2.21E+02	0.00E+00	**-2.21E+02**	**1.26E+06**	**1.26E+06**
1.19E+05	2.61E+03	**1.22E+05**	-6.67E+04	0.00E+00	**-6.67E+04**	**6.58E+08**	**6.58E+08**
1.18E+05	2.61E+03	**1.21E+05**	-6.60E+04	0.00E+00	**-6.60E+04**	**6.53E+08**	**6.53E+08**
1.13E+05	2.60E+03	**1.16E+05**	-6.24E+04	0.00E+00	**-6.24E+04**	**6.20E+08**	**6.20E+08**

Table A5 Bill of Materials Report (Curtain Wall, Minneapolis, MN)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
Aluminum Extrusion	Tons (short)	8.7197	0	0	0	0	8.7197	0	8.7197	Tons (short)
EPDM membrane (black, 60 mil)	lbs	707.5478	0	0	0	0	707.5478	0	0.3538	Tons (short)
FG Batt R11-15	sf (1")	5571.7488	0	0	0	0	5571.749	0	0.1786	Tons (short)
Glazing Panel	Tons (short)	40.7161	0	0	0	0	40.7161	0	40.7161	Tons (short)
Nails	Tons (short)	0.0259	0	0	0	0	0.0259	0	0.0259	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.2941	0	0	0	0	0.2941	0	0.2941	Tons (short)
Spandrel Panel	Tons (short)	1.0936	0	0	0	0	1.0936	0	1.0936	Tons (short)

Table A6 Detailed Summary Measure Table By Life Cycle Stages (Curtain Wall, Minneapolis, MN)

		PRODUCT (A1 to A3)			CONSTRUCTION PROCESS (A4 & A5)			USE (B2, B4 & B6)			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	1.02E+05	5.30E+02	**1.02E+05**	8.28E+02	1.63E+03	**2.45E+03**	4.30E+04	1.44E+03	3.40E+07	**3.40E+07**
Acidification Potential	kg SO2 eq	5.88E+02	5.49E+00	**5.94E+02**	5.99E+00	1.71E+01	**2.31E+01**	2.54E+02	1.49E+01	2.52E+05	**2.52E+05**
HH Particulate	kg PM2.5 eq	8.77E+02	3.00E-01	**8.77E+02**	4.34E-01	9.30E-01	**1.36E+00**	6.97E+02	8.16E-01	2.99E+04	**3.06E+04**
Eutrophication Potential	kg N eq	1.92E+01	3.72E-01	**1.96E+01**	2.45E-01	1.16E+00	**1.40E+00**	1.11E+01	1.01E+00	1.39E+03	**1.41E+03**
Ozone Depletion Potential	kg CFC-11 eq	5.50E-05	2.13E-08	**5.50E-05**	6.14E-07	6.67E-08	**6.81E-07**	3.39E-05	5.79E-08	2.58E-05	**5.97E-05**
Smog Potential	kg O3 eq	8.08E+03	1.91E+02	**8.27E+03**	1.18E+02	5.97E+02	**7.15E+02**	4.67E+03	5.17E+02	4.76E+05	**4.81E+05**
Total Primary Energy	MJ	9.09E+05	7.31E+03	**9.16E+05**	1.04E+04	2.23E+04	**3.27E+04**	3.10E+05	1.96E+04	5.48E+08	**5.49E+08**
Non-Renewable Energy	MJ	8.85E+05	7.30E+03	**8.93E+05**	1.03E+04	2.23E+04	**3.26E+04**	2.96E+05	1.96E+04	5.17E+08	**5.17E+08**
Fossil Fuel Consumption	MJ	8.21E+05	7.29E+03	**8.28E+05**	9.91E+03	2.23E+04	**3.22E+04**	2.61E+05	1.96E+04	4.38E+08	**4.39E+08**

END OF LIFE (C1 to C4)			BEYOND BUILDING LIFE (D)			TOTAL EFFECTS	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
9.28E+03	2.14E+02	**9.49E+03**	-5.12E+03	0.00E+00	**-5.12E+03**	**3.41E+07**	**3.41E+07**
4.39E+01	1.93E+00	**4.58E+01**	-2.36E+01	0.00E+00	**-2.36E+01**	**2.53E+05**	**2.53E+05**
3.63E+00	1.16E-01	**3.74E+00**	-1.92E+00	0.00E+00	**-1.92E+00**	**3.15E+04**	**3.15E+04**

1.11E+00	1.32E-01	**1.24E+00**	-5.32E-01	0.00E+00	**-5.32E-01**	**1.43E+03**	**1.43E+03**
8.81E-07	7.67E-09	**8.89E-07**	-5.05E-07	0.00E+00	**-5.05E-07**	**1.16E-04**	**1.16E-04**
4.76E+02	6.70E+01	**5.43E+02**	-2.21E+02	0.00E+00	**-2.21E+02**	**4.90E+05**	**4.90E+05**
1.19E+05	2.61E+03	**1.22E+05**	-6.67E+04	0.00E+00	**-6.67E+04**	**5.50E+08**	**5.50E+08**
1.18E+05	2.61E+03	**1.21E+05**	-6.60E+04	0.00E+00	**-6.60E+04**	**5.18E+08**	**5.18E+08**
1.13E+05	2.60E+03	**1.16E+05**	-6.24E+04	0.00E+00	**-6.24E+04**	**4.40E+08**	**4.40E+08**

Table A7 Bill of Materials Report (Curtain Wall, Seattle, WA)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
Aluminum Extrusion	Tons (short)	8.7197	0	0	0	0	8.7197	0	8.7197	Tons (short)
EPDM membrane (black, 60 mil)	lbs	707.5478	0	0	0	0	707.5478	0	0.3538	Tons (short)
FG Batt R11-15	sf (1")	5571.7488	0	0	0	0	5571.749	0	0.1786	Tons (short)
Glazing Panel	Tons (short)	40.7161	0	0	0	0	40.7161	0	40.7161	Tons (short)
Nails	Tons (short)	0.0259	0	0	0	0	0.0259	0	0.0259	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.2941	0	0	0	0	0.2941	0	0.2941	Tons (short)
Spandrel Panel	Tons (short)	1.0936	0	0	0	0	1.0936	0	1.0936	Tons (short)

Table A8 Detailed Summary Measure Table By Life Cycle Stages (Curtain Wall, Seattle, WA)

		PRODUCT (A1 to A3)			CONSTRUCTION PROCESS (A4 & A5)			USE (B2, B4 & B6)			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	9.28E+04	4.29E+02	**9.33E+04**	8.24E+02	5.89E+02	**1.41E+03**	3.58E+04	9.86E+02	1.58E+07	**1.58E+07**
Acidification Potential	kg SO2 eq	4.86E+02	4.40E+00	**4.91E+02**	5.96E+00	6.80E+00	**1.28E+01**	1.71E+02	1.01E+01	7.59E+04	**7.61E+04**
HH Particulate	kg PM2.5 eq	8.63E+02	2.38E-01	**8.63E+02**	4.27E-01	3.22E-01	**7.49E-01**	6.86E+02	5.51E-01	5.88E+03	**6.57E+03**
Eutrophication Potential	kg N eq	1.89E+01	2.98E-01	**1.92E+01**	2.45E-01	4.57E-01	**7.02E-01**	1.09E+01	6.84E-01	6.52E+02	**6.63E+02**
Ozone Depletion Potential	kg CFC-11 eq	5.50E-05	1.69E-08	**5.50E-05**	6.14E-07	2.42E-08	**6.38E-07**	3.39E-05	3.90E-08	1.23E-05	**4.63E-05**
Smog Potential	kg O3 eq	7.94E+03	1.53E+02	**8.10E+03**	1.18E+02	2.37E+02	**3.55E+02**	4.56E+03	3.51E+02	1.72E+05	**1.76E+05**
Total Primary Energy	MJ	7.87E+05	6.03E+03	**7.93E+05**	1.04E+04	1.12E+04	**2.15E+04**	2.11E+05	1.37E+04	3.26E+08	**3.27E+08**
Non-Renewable Energy	MJ	6.93E+05	6.03E+03	**6.99E+05**	1.02E+04	1.12E+04	**2.14E+04**	1.39E+05	1.37E+04	1.79E+08	**1.79E+08**
Fossil Fuel Consumption	MJ	6.70E+05	6.02E+03	**6.76E+05**	9.89E+03	1.12E+04	**2.11E+04**	1.37E+05	1.37E+04	1.51E+08	**1.51E+08**

END OF LIFE (C1 to C4)			BEYOND BUILDING LIFE (D)			TOTAL EFFECTS	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
9.27E+03	2.14E+02	**9.49E+03**	-5.12E+03	0.00E+00	**-5.12E+03**	**1.59E+07**	**1.59E+07**
4.38E+01	1.93E+00	**4.57E+01**	-2.36E+01	0.00E+00	**-2.36E+01**	**7.67E+04**	**7.66E+04**

3.62E+00	1.16E-01	**3.74E+00**	-1.92E+00	0.00E+00	**-1.92E+00**	**7.44E+03**	**7.44E+03**
1.11E+00	1.32E-01	**1.24E+00**	-5.32E-01	0.00E+00	**-5.32E-01**	**6.85E+02**	**6.84E+02**
8.81E-07	7.67E-09	**8.89E-07**	-5.05E-07	0.00E+00	**-5.05E-07**	**1.03E-04**	**1.02E-04**
4.76E+02	6.70E+01	**5.43E+02**	-2.21E+02	0.00E+00	**-2.21E+02**	**1.85E+05**	**1.85E+05**
1.19E+05	2.61E+03	**1.22E+05**	-6.67E+04	0.00E+00	**-6.67E+04**	**3.28E+08**	**3.27E+08**
1.18E+05	2.61E+03	**1.21E+05**	-6.60E+04	0.00E+00	**-6.60E+04**	**1.80E+08**	**1.79E+08**
1.13E+05	2.60E+03	**1.15E+05**	-6.24E+04	0.00E+00	**-6.24E+04**	**1.52E+08**	**1.52E+08**

Table A9 Bill of Materials Report (Curtain Wall, Los Angeles, CA)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
Aluminum Extrusion	Tons (short)	8.7197	0	0	0	0	8.7197	0	8.7197	Tons (short)
EPDM membrane (black, 60 mil)	lbs	707.5478	0	0	0	0	707.5478	0	0.3538	Tons (short)
FG Batt R11-15	sf (1")	5571.7488	0	0	0	0	5571.749	0	0.1786	Tons (short)
Glazing Panel	Tons (short)	40.7161	0	0	0	0	40.7161	0	40.7161	Tons (short)
Nails	Tons (short)	0.0259	0	0	0	0	0.0259	0	0.0259	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.2941	0	0	0	0	0.2941	0	0.2941	Tons (short)
Spandrel Panel	Tons (short)	1.0936	0	0	0	0	1.0936	0	1.0936	Tons (short)

Table A10 Detailed Summary Measure Table By Life Cycle Stages (Curtain Wall, Los Angeles, CA)

		PRODUCT (A1 to A3)			**CONSTRUCTION PROCESS (A4 & A5)**			**USE (B2, B4 & B6)**			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	1.01E+05	5.04E+02	**1.02E+05**	8.24E+02	7.06E+03	**7.88E+03**	4.26E+04	4.22E+03	3.01E+07	**3.01E+07**
Acidification Potential	kg SO2 eq	5.84E+02	5.07E+00	**5.89E+02**	5.97E+00	7.44E+01	**8.04E+01**	2.51E+02	4.40E+01	2.28E+05	**2.29E+05**
HH Particulate	kg PM2.5 eq	8.73E+02	2.81E-01	**8.73E+02**	4.27E-01	4.03E+00	**4.46E+00**	6.95E+02	2.40E+00	1.65E+04	**1.72E+04**
Eutrophication Potential	kg N eq	1.96E+01	3.44E-01	**1.99E+01**	2.45E-01	5.03E+00	**5.28E+00**	1.15E+01	2.98E+00	2.20E+03	**2.21E+03**
Ozone Depletion Potential	kg CFC-11 eq	5.50E-05	1.97E-08	**5.50E-05**	6.14E-07	2.90E-07	**9.04E-07**	3.39E-05	1.72E-07	6.15E-05	**9.56E-05**
Smog Potential	kg O3 eq	8.21E+03	1.77E+02	**8.39E+03**	1.18E+02	2.59E+03	**2.71E+03**	4.78E+03	1.53E+03	6.13E+05	**6.20E+05**
Total Primary Energy	MJ	9.10E+05	6.88E+03	**9.17E+05**	1.04E+04	9.68E+04	**1.07E+05**	3.11E+05	5.75E+04	5.55E+08	**5.55E+08**
Non-Renewable Energy	MJ	8.79E+05	6.87E+03	**8.86E+05**	1.03E+04	9.68E+04	**1.07E+05**	2.91E+05	5.75E+04	5.02E+08	**5.02E+08**
Fossil Fuel Consumption	MJ	8.33E+05	6.86E+03	**8.40E+05**	9.91E+03	9.66E+04	**1.07E+05**	2.71E+05	5.74E+04	4.74E+08	**4.74E+08**

END OF LIFE (C1 to C4)			**BEYOND BUILDING LIFE (D)**			**TOTAL EFFECTS**	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
9.28E+03	2.14E+02	**9.49E+03**	-5.12E+03	0.00E+00	**-5.12E+03**	**3.03E+07**	**3.02E+07**
4.38E+01	1.93E+00	**4.58E+01**	-2.36E+01	0.00E+00	**-2.36E+01**	**2.29E+05**	**2.29E+05**

3.63E+00	1.16E-01	**3.74E+00**	-1.92E+00	0.00E+00	**-1.92E+00**	**1.80E+04**	**1.80E+04**
1.11E+00	1.32E-01	**1.24E+00**	-5.32E-01	0.00E+00	**-5.32E-01**	**2.24E+03**	**2.24E+03**
8.81E-07	7.67E-09	**8.89E-07**	-5.05E-07	0.00E+00	**-5.05E-07**	**1.52E-04**	**1.52E-04**
4.76E+02	6.70E+01	**5.43E+02**	-2.21E+02	0.00E+00	**-2.21E+02**	**6.31E+05**	**6.31E+05**
1.19E+05	2.61E+03	**1.22E+05**	-6.67E+04	0.00E+00	**-6.67E+04**	**5.56E+08**	**5.56E+08**
1.18E+05	2.61E+03	**1.21E+05**	-6.60E+04	0.00E+00	**-6.60E+04**	**5.04E+08**	**5.03E+08**
1.13E+05	2.60E+03	**1.16E+05**	-6.24E+04	0.00E+00	**-6.24E+04**	**4.75E+08**	**4.75E+08**

Table A11 Bill of Materials Report (Brick Veneer, Pittsburgh, PA)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
1/2" Regular Gypsum Board	sf	5684.7997	0	0	0	0	5684.8	0	4.6923	Tons (short)
3 mil Polyethylene	sf	5482.2141	0	0	0	0	5482.214	0	0.0421	Tons (short)
Air Barrier	sf	5482.2141	0	0	0	0	5482.214	0	0.0343	Tons (short)
Aluminum Extrusion	Tons (short)	0.3434	0	0	0	0	0.3434	0	0.3434	Tons (short)
Aluminum Window Frame	lbs	2971.6659	0	0	0	0	2971.666	0	1.4858	Tons (short)
Cold Rolled Sheet	Tons (short)	0.1069	0	0	0	0	0.1069	0	0.1069	Tons (short)
Double Glazed Soft Coated Air	sf	4962.2602	0	0	0	0	4962.26	0	8.2289	Tons (short)
Extruded Polystyrene	sf (1")	10749.4272	0	0	0	0	10749.43	0	1.354	Tons (short)
Galvanize	Tons	2.3266	0	0	0	0	2.3266	0	2.326	Tons

d Studs	(short)								6	(short)
Glazing Panel	Tons (short)	0.6706	0	0	0	0	0.6706	0	0.6706	Tons (short)
Joint Compound	Tons (short)	0.581	0	0	0	0	0.581	0	0.581	Tons (short)
Mortar	yd3	18.28	0	0	0	0	18.28	0	19.7197	Tons (short)
Nails	Tons (short)	0.064	0	0	0	0	0.064	0	0.064	Tons (short)
Ontario (Standard) Brick	sf	5426.3997	0	0	0	0	5426.4	0	67.2405	Tons (short)
Oriented Strand Board	msf (3/8")	7.2172	0	0	0	0	7.2172	0	4.4629	Tons (short)
Paper Tape	Tons (short)	0.0067	0	0	0	0	0.0067	0	0.0067	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.026	0	0	0	0	0.026	0	0.026	Tons (short)
Water Based Latex Paint	Gallons (us)	180.0855	0	0	0	0	180.0855	0	0.5636	Tons (short)

Table A12 Detailed Summary Measure Table By Life Cycle Stages (Brick Veneer, Pittsburgh, PA)

		PRODUCT (A1 to A3)			CONSTRUCTION PROCESS (A4 & A5)			USE (B2, B4 & B6)			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	3.65E+04	5.80E+02	**3.70E+04**	1.74E+03	2.26E+03	**4.01E+03**	2.78E+04	6.55E+02	3.46E+07	**3.47E+07**
Acidification Potential	kg SO2 eq	2.70E+02	5.39E+00	**2.75E+02**	1.23E+01	2.38E+01	**3.61E+01**	2.10E+02	6.75E+00	2.95E+05	**2.95E+05**
HH Particulate	kg PM2.5 eq	5.01E+01	3.14E-01	**5.04E+01**	2.30E+00	1.28E+00	**3.58E+00**	4.01E+01	3.71E-01	3.04E+04	**3.05E+04**
Eutrophication Potential	kg N eq	7.93E+00	3.67E-01	**8.30E+00**	3.55E-01	1.61E+00	**1.97E+00**	5.57E+00	4.57E-01	3.54E+03	**3.54E+03**

Ozone Depletion Potential	kg CFC-11 eq	2.30E-04	2.11E-08	**2.30E-04**	4.66E-06	9.19E-08	**4.75E-06**	5.87E-04	2.63E-08	1.85E-05	**6.06E-04**
Smog Potential	kg O_3 eq	2.47E+03	1.87E+02	**2.66E+03**	1.14E+02	8.30E+02	**9.43E+02**	1.53E+03	2.35E+02	1.62E+06	**1.62E+06**
Total Primary Energy	MJ	5.38E+05	7.55E+03	**5.45E+05**	2.41E+04	3.21E+04	**5.62E+04**	3.32E+05	8.86E+03	5.86E+08	**5.86E+08**
Non-Renewable Energy	MJ	5.16E+05	7.55E+03	**5.24E+05**	2.31E+04	3.21E+04	**5.52E+04**	3.29E+05	8.85E+03	5.81E+08	**5.81E+08**
Fossil Fuel Consumption	MJ	4.82E+05	7.53E+03	**4.90E+05**	2.14E+04	3.20E+04	**5.34E+04**	3.13E+05	8.83E+03	4.66E+08	**4.66E+08**

END OF LIFE (C1 to C4)			**BEYOND BUILDING LIFE (D)**			**TOTAL EFFECTS**	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
9.11E+02	6.32E+02	**1.54E+03**	-1.59E+06	0.00E+00	**-1.59E+06**	**3.47E+07**	**3.31E+07**
6.37E+00	5.70E+00	**1.21E+01**	-7.20E+03	0.00E+00	**-7.20E+03**	**2.96E+05**	**2.89E+05**
6.12E-01	3.42E-01	**9.54E-01**	-6.18E+02	0.00E+00	**-6.18E+02**	**3.05E+04**	**2.99E+04**
2.82E-01	3.90E-01	**6.72E-01**	-1.65E+02	0.00E+00	**-1.65E+02**	**3.56E+03**	**3.39E+03**
6.75E-08	2.27E-08	**9.02E-08**	-1.52E-04	0.00E+00	**-1.52E-04**	**8.40E-04**	**6.88E-04**
1.41E+02	1.98E+02	**3.39E+02**	-6.76E+04	0.00E+00	**-6.76E+04**	**1.63E+06**	**1.56E+06**
1.24E+04	7.72E+03	**2.02E+04**	-2.03E+07	0.00E+00	**-2.03E+07**	**5.87E+08**	**5.66E+08**
1.23E+04	7.71E+03	**2.01E+04**	-2.01E+07	0.00E+00	**-2.01E+07**	**5.82E+08**	**5.62E+08**
1.18E+04	7.70E+03	**1.95E+04**	-1.92E+07	0.00E+00	**-1.92E+07**	**4.66E+08**	**4.47E+08**

Table A13 Bill of Materials Report (Brick Veneer, Orlando, FL)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
1/2" Regular Gypsum Board	sf	5684.7997	0	0	0	0	5684.8	0	4.6923	Tons (short)
3 mil Polyethylene	sf	5482.2141	0	0	0	0	5482.214	0	0.0421	Tons (short)
Air Barrier	sf	5482.2141	0	0	0	0	5482.214	0	0.0343	Tons (short)
Aluminum Extrusion	Tons (short)	0.3434	0	0	0	0	0.3434	0	0.3434	Tons (short)
Aluminum Window Frame	lbs	2971.6659	0	0	0	0	2971.666	0	1.4858	Tons (short)
Cold Rolled Sheet	Tons (short)	0.1069	0	0	0	0	0.1069	0	0.1069	Tons (short)
Double Glazed Soft Coated Air	sf	4962.2602	0	0	0	0	4962.26	0	8.2289	Tons (short)
Extruded Polystyrene	sf (1")	10749.4272	0	0	0	0	10749.43	0	1.354	Tons (short)
Galvanized Studs	Tons (short)	2.3266	0	0	0	0	2.3266	0	2.3266	Tons (short)
Glazing Panel	Tons (short)	0.6706	0	0	0	0	0.6706	0	0.6706	Tons (short)
Joint Compound	Tons (short)	0.581	0	0	0	0	0.581	0	0.581	Tons (short)
Mortar	yd3	18.28	0	0	0	0	18.28	0	19.7197	Tons (short)
Nails	Tons (short)	0.064	0	0	0	0	0.064	0	0.064	Tons (short)
Ontario (Standard) Brick	sf	5426.3997	0	0	0	0	5426.4	0	67.2405	Tons (short)
Oriented Strand Board	msf (3/8")	7.2172	0	0	0	0	7.2172	0	4.4629	Tons (short)

Paper Tape	Tons (short)	0.0067	0	0	0	0	0.0067	0	0.0067	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.026	0	0	0	0	0.026	0	0.026	Tons (short)
Water Based Latex Paint	Gallons (us)	180.0855	0	0	0	0	180.0855	0	0.5636	Tons (short)

Table A14 Detailed Summary Measure Table By Life Cycle Stages (Brick Veneer, Orlando, FL)

		PRODUCT (A1 to A3)			**CONSTRUCTION PROCESS (A4 & A5)**			**USE (B2, B4 & B6)**			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	3.71E+04	5.74E+02	**3.77E+04**	1.81E+03	6.18E+03	**7.99E+03**	2.80E+04	7.24E+02	3.96E+07	**3.97E+07**
Acidification Potential	kg SO2 eq	2.74E+02	5.28E+00	**2.79E+02**	1.27E+01	6.47E+01	**7.75E+01**	2.11E+02	7.51E+00	3.28E+05	**3.28E+05**
HH Particulate	kg PM2.5 eq	4.93E+01	3.12E-01	**4.96E+01**	2.24E+00	3.53E+00	**5.77E+00**	3.97E+01	4.11E-01	2.65E+04	**2.65E+04**
Eutrophication Potential	kg N eq	7.93E+00	3.60E-01	**8.29E+00**	3.56E-01	4.38E+00	**4.73E+00**	5.52E+00	5.08E-01	3.50E+03	**3.50E+03**
Ozone Depletion Potential	kg CFC-11 eq	2.30E-04	2.09E-08	**2.30E-04**	4.69E-06	2.53E-07	**4.94E-06**	5.87E-04	2.93E-08	4.38E-05	**6.31E-04**
Smog Potential	kg O3 eq	2.39E+03	1.83E+02	**2.57E+03**	1.08E+02	2.25E+03	**2.36E+03**	1.49E+03	2.61E+02	1.25E+06	**1.25E+06**
Total Primary Energy	MJ	5.46E+05	7.25E+03	**5.53E+05**	2.50E+04	8.39E+04	**1.09E+05**	3.36E+05	9.83E+03	6.57E+08	**6.57E+08**
Non-Renewable Energy	MJ	5.25E+05	7.25E+03	**5.32E+05**	2.39E+04	8.39E+04	**1.08E+05**	3.33E+05	9.83E+03	6.51E+08	**6.52E+08**
Fossil Fuel Consumption	MJ	4.98E+05	7.23E+03	**5.05E+05**	2.32E+04	8.37E+04	**1.07E+05**	3.20E+05	9.81E+03	6.19E+08	**6.19E+08**

END OF LIFE (C1 to C4)	**BEYOND BUILDING LIFE (D)**	**TOTAL EFFECTS**

De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
9.22E+02	6.32E+02	**1.55E+03**	-1.59E+06	0.00E+00	**-1.59E+06**	**3.97E+07**	**3.81E+07**
6.44E+00	5.70E+00	**1.21E+01**	-7.20E+03	0.00E+00	**-7.20E+03**	**3.28E+05**	**3.21E+05**
6.04E-01	3.42E-01	**9.46E-01**	-6.18E+02	0.00E+00	**-6.18E+02**	**2.66E+04**	**2.60E+04**
2.82E-01	3.90E-01	**6.72E-01**	-1.65E+02	0.00E+00	**-1.65E+02**	**3.52E+03**	**3.35E+03**
6.76E-08	2.27E-08	**9.03E-08**	-1.52E-04	0.00E+00	**-1.52E-04**	**8.66E-04**	**7.14E-04**
1.41E+02	1.98E+02	**3.39E+02**	-6.76E+04	0.00E+00	**-6.76E+04**	**1.25E+06**	**1.18E+06**
1.26E+04	7.72E+03	**2.03E+04**	-2.03E+07	0.00E+00	**-2.03E+07**	**6.58E+08**	**6.38E+08**
1.25E+04	7.71E+03	**2.02E+04**	-2.01E+07	0.00E+00	**-2.01E+07**	**6.52E+08**	**6.32E+08**
1.21E+04	7.70E+03	**1.98E+04**	-1.92E+07	0.00E+00	**-1.92E+07**	**6.20E+08**	**6.01E+08**

Table A15 Bill of Materials Report (Brick Veneer, Minneapolis, MN)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
1/2" Regular Gypsum Board	sf	5684.7997	0	0	0	0	5684.8	0	4.6923	Tons (short)
3 mil Polyethylene	sf	5482.2141	0	0	0	0	5482.214	0	0.0421	Tons (short)
Air Barrier	sf	5482.2141	0	0	0	0	5482.214	0	0.0343	Tons (short)
Aluminum Extrusion	Tons (short)	0.3434	0	0	0	0	0.3434	0	0.3434	Tons (short)
Aluminum	lbs	2971.665	0	0	0	0	2971.6	0	1.485	Tons

Window Frame		9					66		8	(short)
Cold Rolled Sheet	Tons (short)	0.1069	0	0	0	0	0.1069	0	0.1069	Tons (short)
Double Glazed Soft Coated Air	sf	4962.2602	0	0	0	0	4962.26	0	8.2289	Tons (short)
Extruded Polystyrene	sf (1")	10749.4272	0	0	0	0	10749.43	0	1.354	Tons (short)
Galvanized Studs	Tons (short)	2.3266	0	0	0	0	2.3266	0	2.3266	Tons (short)
Glazing Panel	Tons (short)	0.6706	0	0	0	0	0.6706	0	0.6706	Tons (short)
Joint Compound	Tons (short)	0.581	0	0	0	0	0.581	0	0.581	Tons (short)
Mortar	yd3	18.28	0	0	0	0	18.28	0	19.7197	Tons (short)
Nails	Tons (short)	0.064	0	0	0	0	0.064	0	0.064	Tons (short)
Ontario (Standard) Brick	sf	5426.3997	0	0	0	0	5426.4	0	67.2405	Tons (short)
Oriented Strand Board	msf (3/8")	7.2172	0	0	0	0	7.2172	0	4.4629	Tons (short)
Paper Tape	Tons (short)	0.0067	0	0	0	0	0.0067	0	0.0067	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.026	0	0	0	0	0.026	0	0.026	Tons (short)
Water Based Latex Paint	Gallons (us)	180.0855	0	0	0	0	180.0855	0	0.5636	Tons (short)

Table A16 Detailed Summary Measure Table By Life Cycle Stages (Brick Veneer, Minneapolis, MN)

		PRODUCT (A1 to A3)			CONSTRUCTION PROCESS (A4 & A5)			USE (B2, B4 & B6)			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	3.62E+04	6.26E+02	**3.68E+04**	1.73E+03	1.81E+03	**3.54E+03**	2.73E+04	6.27E+02	3.40E+07	**3.40E+07**
Acidification Potential	kg SO2 eq	2.63E+02	5.95E+00	**2.69E+02**	1.18E+01	1.75E+01	**2.92E+01**	2.02E+02	6.44E+00	2.52E+05	**2.52E+05**
HH Particulate	kg PM2.5 eq	4.94E+01	3.43E-01	**4.97E+01**	2.27E+00	9.95E-01	**3.26E+00**	3.98E+01	3.55E-01	2.99E+04	**3.00E+04**
Eutrophication Potential	kg N eq	7.66E+00	4.05E-01	**8.07E+00**	3.31E-01	1.19E+00	**1.52E+00**	5.31E+00	4.36E-01	1.39E+03	**1.40E+03**
Ozone Depletion Potential	kg CFC-11 eq	2.30E-04	2.34E-08	**2.30E-04**	4.69E-06	6.83E-08	**4.76E-06**	5.87E-04	2.52E-08	2.58E-05	**6.13E-04**
Smog Potential	kg O3 eq	2.29E+03	2.07E+02	**2.50E+03**	9.89E+01	6.08E+02	**7.06E+02**	1.40E+03	2.24E+02	4.76E+05	**4.77E+05**
Total Primary Energy	MJ	5.32E+05	8.19E+03	**5.40E+05**	2.37E+04	2.38E+04	**4.75E+04**	3.25E+05	8.43E+03	5.48E+08	**5.49E+08**
Non-Renewable Energy	MJ	5.06E+05	8.19E+03	**5.14E+05**	2.23E+04	2.38E+04	**4.61E+04**	3.19E+05	8.43E+03	5.17E+08	**5.17E+08**
Fossil Fuel Consumption	MJ	4.74E+05	8.17E+03	**4.83E+05**	2.10E+04	2.38E+04	**4.48E+04**	3.03E+05	8.41E+03	4.38E+08	**4.39E+08**

END OF LIFE (C1 to C4)			BEYOND BUILDING LIFE (D)			TOTAL EFFECTS	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
9.10E+02	6.32E+02	**1.54E+03**	-1.59E+06	0.00E+00	**-1.59E+06**	**3.40E+07**	**3.24E+07**
6.28E+00	5.70E+00	**1.20E+01**	-7.20E+03	0.00E+00	**-7.20E+03**	**2.52E+05**	**2.45E+05**

6.11E-01	3.42E-01	**9.53E-01**	-6.18E+02	0.00E+00	**-6.18E+02**	**3.00E+04**	**2.94E+04**
2.77E-01	3.90E-01	**6.67E-01**	-1.65E+02	0.00E+00	**-1.65E+02**	**1.41E+03**	**1.25E+03**
6.75E-08	2.27E-08	**9.02E-08**	-1.52E-04	0.00E+00	**-1.52E-04**	**8.48E-04**	**6.96E-04**
1.39E+02	1.98E+02	**3.37E+02**	-6.76E+04	0.00E+00	**-6.76E+04**	**4.81E+05**	**4.13E+05**
1.24E+04	7.72E+03	**2.01E+04**	-2.03E+07	0.00E+00	**-2.03E+07**	**5.49E+08**	**5.29E+08**
1.22E+04	7.71E+03	**1.99E+04**	-2.01E+07	0.00E+00	**-2.01E+07**	**5.18E+08**	**4.98E+08**
1.17E+04	7.70E+03	**1.94E+04**	-1.92E+07	0.00E+00	**-1.92E+07**	**4.39E+08**	**4.20E+08**

Table A17 Bill of Materials Report (Brick Veneer, Seattle, WA)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
1/2" Regular Gypsum Board	sf	5684.7997	0	0	0	0	5684.8	0	4.6923	Tons (short)
3 mil Polyethylene	sf	5482.2141	0	0	0	0	5482.214	0	0.0421	Tons (short)
Air Barrier	sf	5482.2141	0	0	0	0	5482.214	0	0.0343	Tons (short)
Aluminum Extrusion	Tons (short)	0.3434	0	0	0	0	0.3434	0	0.3434	Tons (short)
Aluminum Window Frame	lbs	2971.6659	0	0	0	0	2971.666	0	1.4858	Tons (short)
Cold Rolled Sheet	Tons (short)	0.1069	0	0	0	0	0.1069	0	0.1069	Tons (short)
Double Glazed Soft Coated Air	sf	4962.2602	0	0	0	0	4962.26	0	8.2289	Tons (short)
Extruded Polystyrene	sf (1")	10749.4272	0	0	0	0	10749.43	0	1.354	Tons (short)
Galvanize	Tons	1.1659	0	0	0	0	1.1659	0	1.165	Tons

d Sheet	(short)								9	(short)
Galvanized Studs	Tons (short)	2.3266	0	0	0	0	2.3266	0	2.3266	Tons (short)
Glazing Panel	Tons (short)	0.6706	0	0	0	0	0.6706	0	0.6706	Tons (short)
Joint Compound	Tons (short)	0.581	0	0	0	0	0.581	0	0.581	Tons (short)
Mortar	yd3	18.28	0	0	0	0	18.28	0	19.7197	Tons (short)
Nails	Tons (short)	0.064	0	0	0	0	0.064	0	0.064	Tons (short)
Ontario (Standard) Brick	sf	5426.3997	0	0	0	0	5426.4	0	67.2405	Tons (short)
Oriented Strand Board	msf (3/8")	7.2172	0	0	0	0	7.2172	0	4.4629	Tons (short)
Paper Tape	Tons (short)	0.0067	0	0	0	0	0.0067	0	0.0067	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.026	0	0	0	0	0.026	0	0.026	Tons (short)
Water Based Latex Paint	Gallons (us)	180.0855	0	0	0	0	180.0855	0	0.5636	Tons (short)

Table A18 Detailed Summary Measure Table By Life Cycle Stages (Brick Veneer, Seattle, WA)

		PRODUCT (A1 to A3)			CONSTRUCTION PROCESS (A4 & A5)			USE (B2, B4 & B6)			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	3.50E+04	5.36E+02	**3.55E+04**	1.50E+03	7.85E+02	**2.28E+03**	2.46E+04	6.40E+02	1.58E+07	**1.58E+07**
Acidification Potential	kg SO2 eq	2.38E+02	5.06E+00	**2.43E+02**	9.40E+00	8.43E+00	**1.78E+01**	1.71E+02	6.73E+00	7.59E+04	**7.61E+04**
HH Particulate	kg PM2.5 eq	5.00E+01	2.92E-01	**5.03E+01**	2.08E+00	4.22E-01	**2.51E+00**	3.56E+01	3.60E-01	5.88E+03	**5.92E+03**

Eutrophication Potential	kg N eq	7.75E+00	3.45E-01	**8.09E+00**	3.13E-01	5.69E-01	**8.82E-01**	5.21E+00	4.55E-01	6.52E+02	**6.58E+02**
Ozone Depletion Potential	kg CFC-11 eq	2.27E-04	1.98E-08	**2.27E-04**	4.52E-06	3.05E-08	**4.55E-06**	5.87E-04	2.58E-08	1.23E-05	**5.99E-04**
Smog Potential	kg O3 eq	2.49E+03	1.76E+02	**2.66E+03**	1.00E+02	2.94E+02	**3.94E+02**	1.36E+03	2.34E+02	1.72E+05	**1.73E+05**
Total Primary Energy	MJ	5.29E+05	7.12E+03	**5.36E+05**	2.13E+04	1.38E+04	**3.51E+04**	2.88E+05	9.27E+03	3.26E+08	**3.27E+08**
Non-Renewable Energy	MJ	4.83E+05	7.12E+03	**4.90E+05**	1.84E+04	1.38E+04	**3.22E+04**	2.61E+05	9.26E+03	1.79E+08	**1.79E+08**
Fossil Fuel Consumption	MJ	4.56E+05	7.10E+03	**4.64E+05**	1.78E+04	1.38E+04	**3.16E+04**	2.57E+05	9.25E+03	1.51E+08	**1.51E+08**

END OF LIFE (C1 to C4)			**BEYOND BUILDING LIFE (D)**			**TOTAL EFFECTS**	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
9.19E+02	6.32E+02	**1.55E+03**	-1.59E+06	0.00E+00	**-1.59E+06**	**1.59E+07**	**1.43E+07**
6.26E+00	5.70E+00	**1.20E+01**	-7.20E+03	0.00E+00	**-7.20E+03**	**7.64E+04**	**6.92E+04**
6.85E-01	3.42E-01	**1.03E+00**	-6.19E+02	0.00E+00	**-6.19E+02**	**5.97E+03**	**5.35E+03**
2.98E-01	3.90E-01	**6.88E-01**	-1.65E+02	0.00E+00	**-1.65E+02**	**6.67E+02**	**5.02E+02**
6.92E-08	2.27E-08	**9.18E-08**	-1.52E-04	0.00E+00	**-1.52E-04**	**8.31E-04**	**6.79E-04**
1.50E+02	1.98E+02	**3.48E+02**	-6.76E+04	0.00E+00	**-6.76E+04**	**1.77E+05**	**1.09E+05**
1.27E+04	7.72E+03	**2.04E+04**	-2.03E+07	0.00E+00	**-2.03E+07**	**3.27E+08**	**3.07E+08**
1.21E+04	7.71E+03	**1.98E+04**	-2.01E+07	0.00E+00	**-2.01E+07**	**1.79E+08**	**1.59E+08**
1.17E+04	7.70E+03	**1.94E+04**	-1.92E+07	0.00E+00	**-1.92E+07**	**1.52E+08**	**1.33E+08**

Table A19 Bill of Materials Report (Brick Veneer, Los Angeles, CA)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
1/2" Regular Gypsum Board	sf	5684.7997	0	0	0	0	5684.8	0	4.6923	Tons (short)
3 mil Polyethylene	sf	5482.2141	0	0	0	0	5482.214	0	0.0421	Tons (short)
Air Barrier	sf	5482.2141	0	0	0	0	5482.214	0	0.0343	Tons (short)
Aluminum Extrusion	Tons (short)	0.3434	0	0	0	0	0.3434	0	0.3434	Tons (short)
Aluminum Window Frame	lbs	2971.6659	0	0	0	0	2971.666	0	1.4858	Tons (short)
Cold Rolled Sheet	Tons (short)	0.1069	0	0	0	0	0.1069	0	0.1069	Tons (short)
Double Glazed Soft Coated Air	sf	4962.2602	0	0	0	0	4962.26	0	8.2289	Tons (short)
Extruded Polystyrene	sf (1")	10749.4272	0	0	0	0	10749.43	0	1.354	Tons (short)
Galvanized Sheet	Tons (short)	1.1659	0	0	0	0	1.1659	0	1.1659	Tons (short)
Galvanized Studs	Tons (short)	2.3266	0	0	0	0	2.3266	0	2.3266	Tons (short)
Glazing Panel	Tons (short)	0.6706	0	0	0	0	0.6706	0	0.6706	Tons (short)
Joint Compound	Tons (short)	0.581	0	0	0	0	0.581	0	0.581	Tons (short)
Mortar	yd3	18.28	0	0	0	0	18.28	0	19.7197	Tons (short)
Nails	Tons (short)	0.064	0	0	0	0	0.064	0	0.064	Tons (short)
Ontario (Standard) Brick	sf	5426.3997	0	0	0	0	5426.4	0	67.2405	Tons (short)

Oriented Strand Board	msf (3/8")	7.2172	0	0	0	0	7.2172	0	4.4629	Tons (short)
Paper Tape	Tons (short)	0.0067	0	0	0	0	0.0067	0	0.0067	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.026	0	0	0	0	0.026	0	0.026	Tons (short)
Water Based Latex Paint	Gallons (us)	180.0855	0	0	0	0	180.0855	0	0.5636	Tons (short)

Table A20 Detailed Summary Measure Table By Life Cycle Stages (Brick Veneer, Los Angeles, CA)

		PRODUCT (A1 to A3)			**CONSTRUCTION PROCESS (A4 & A5)**			**USE (B2, B4 & B6)**			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	3.79E+04	5.28E+02	**3.84E+04**	1.71E+03	8.52E+03	**1.02E+04**	2.69E+04	1.62E+03	3.01E+07	**3.01E+07**
Acidification Potential	kg SO2 eq	2.69E+02	4.92E+00	**2.74E+02**	1.15E+01	9.17E+01	**1.03E+02**	1.99E+02	1.69E+01	2.28E+05	**2.29E+05**
HH Particulate	kg PM2.5 eq	5.14E+01	2.86E-01	**5.17E+01**	2.18E+00	4.80E+00	**6.99E+00**	3.84E+01	9.21E-01	1.65E+04	**1.65E+04**
Eutrophication Potential	kg N eq	8.12E+00	3.36E-01	**8.45E+00**	3.40E-01	6.19E+00	**6.53E+00**	5.40E+00	1.14E+00	2.20E+03	**2.20E+03**
Ozone Depletion Potential	kg CFC-11 eq	2.29E-04	1.93E-08	**2.29E-04**	4.62E-06	3.48E-07	**4.97E-06**	5.87E-04	6.58E-08	6.15E-05	**6.49E-04**
Smog Potential	kg O3 eq	2.51E+03	1.71E+02	**2.69E+03**	1.03E+02	3.20E+03	**3.30E+03**	1.43E+03	5.87E+02	6.13E+05	**6.15E+05**
Total Primary Energy	MJ	5.67E+05	6.98E+03	**5.74E+05**	2.42E+04	1.29E+05	**1.53E+05**	3.24E+05	2.19E+04	5.55E+08	**5.55E+08**
Non-Renewable Energy	MJ	5.39E+05	6.98E+03	**5.46E+05**	2.25E+04	1.29E+05	**1.51E+05**	3.15E+05	2.19E+04	5.02E+08	**5.02E+08**
Fossil Fuel Consumption	MJ	5.08E+05	6.97E+03	**5.15E+05**	2.18E+04	1.28E+05	**1.50E+05**	3.04E+05	2.19E+04	4.74E+08	**4.74E+08**

END OF LIFE (C1 to C4)			BEYOND BUILDING LIFE (D)			TOTAL EFFECTS	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
9.64E+02	6.32E+02	**1.60E+03**	-1.59E+06	0.00E+00	**-1.59E+06**	**3.02E+07**	**2.86E+07**
6.74E+00	5.70E+00	**1.24E+01**	-7.20E+03	0.00E+00	**-7.20E+03**	**2.29E+05**	**2.22E+05**
7.19E-01	3.42E-01	**1.06E+00**	-6.19E+02	0.00E+00	**-6.19E+02**	**1.66E+04**	**1.59E+04**
3.03E-01	3.90E-01	**6.93E-01**	-1.65E+02	0.00E+00	**-1.65E+02**	**2.22E+03**	**2.06E+03**
6.93E-08	2.27E-08	**9.20E-08**	-1.52E-04	0.00E+00	**-1.52E-04**	**8.83E-04**	**7.31E-04**
1.51E+02	1.98E+02	**3.49E+02**	-6.76E+04	0.00E+00	**-6.76E+04**	**6.22E+05**	**5.54E+05**
1.34E+04	7.72E+03	**2.11E+04**	-2.03E+07	0.00E+00	**-2.03E+07**	**5.56E+08**	**5.35E+08**
1.31E+04	7.71E+03	**2.08E+04**	-2.01E+07	0.00E+00	**-2.01E+07**	**5.03E+08**	**4.83E+08**
1.27E+04	7.70E+03	**2.04E+04**	-1.92E+07	0.00E+00	**-1.92E+07**	**4.75E+08**	**4.56E+08**

Table A21 Bill of Materials Report (Precast Concrete Panel, Pittsburgh, PA)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
1/2" Regular Gypsum Board	sf	4414.2997	0	0	0	0	4414.3	0	3.6436	Tons (short)
3 mil Polyethylene	sf	4256.9901	0	0	0	0	4256.99	0	0.0327	Tons (short)
Air Barrier	sf	4256.9901	0	0	0	0	4256.99	0	0.0266	Tons (short)

Aluminum Extrusion	Tons (short)	0.3434	0	0	0	0	0.3434	0	0.3434	Tons (short)
Aluminum Window Frame	lbs	5306.5462	0	0	0	0	5306.546	0	2.6533	Tons (short)
Double Glazed Soft Coated Air	sf	8860.6071	0	0	0	0	8860.607	0	14.6936	Tons (short)
Extruded Polystyrene	sf (1")	8347.03	0	0	0	0	8347.03	0	1.0514	Tons (short)
Galvanized Studs	Tons (short)	2.3419	0	0	0	0	2.3419	0	2.3419	Tons (short)
Glazing Panel	Tons (short)	0.6706	0	0	0	0	0.6706	0	0.6706	Tons (short)
Joint Compound	Tons (short)	0.4512	0	0	0	0	0.4512	0	0.4512	Tons (short)
Nails	Tons (short)	0.0555	0	0	0	0	0.0555	0	0.0555	Tons (short)
Oriented Strand Board	msf (3/8")	5.6042	0	0	0	0	5.6042	0	3.4655	Tons (short)
Paper Tape	Tons (short)	0.0052	0	0	0	0	0.0052	0	0.0052	Tons (short)
Precast Insulated Panel	sf	4253.7797	0	0	0	0	4253.78	0	131.3834	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.026	0	0	0	0	0.026	0	0.026	Tons (short)
Water Based Latex Paint	Gallons (us)	139.8381	0	0	0	0	139.8381	0	0.4376	Tons (short)

Table A22 Detailed Summary Measure Table By Life Cycle Stages (Precast Concrete Panel, Pittsburgh, PA)

		PRODUCT (A1 to A3)			CONSTRUCTION PROCESS (A4 & A5)			USE (B2, B4 & B6)			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	6.00E+04	8.46E+02	**6.08E+04**	5.73E+02	1.75E+03	**2.32E+03**	4.77E+04	1.13E+03	3.46E+07	**3.47E+07**
Acidification Potential	kg SO2 eq	3.64E+02	7.92E+00	**3.72E+02**	3.42E+00	1.69E+01	**2.04E+01**	3.64E+02	1.16E+01	2.95E+05	**2.96E+05**
HH Particulate	kg PM2.5 eq	6.53E+01	4.57E-01	**6.58E+01**	5.10E-01	9.61E-01	**1.47E+00**	5.03E+01	6.38E-01	3.04E+04	**3.05E+04**
Eutrophication Potential	kg N eq	1.10E+01	5.40E-01	**1.15E+01**	1.63E-01	1.15E+00	**1.32E+00**	9.61E+00	7.86E-01	3.54E+03	**3.55E+03**
Ozone Depletion Potential	kg CFC-11 eq	2.51E-03	3.09E-08	**2.51E-03**	3.06E-07	6.60E-08	**3.72E-07**	1.05E-03	4.53E-08	1.85E-05	**1.07E-03**
Smog Potential	kg O3 eq	3.77E+03	2.75E+02	**4.04E+03**	3.61E+01	5.89E+02	**6.25E+02**	2.59E+03	4.04E+02	1.62E+06	**1.62E+06**
Total Primary Energy	MJ	6.85E+05	1.14E+04	**6.97E+05**	9.50E+03	2.34E+04	**3.29E+04**	5.62E+05	1.52E+04	5.86E+08	**5.86E+08**
Non-Renewable Energy	MJ	6.67E+05	1.14E+04	**6.78E+05**	8.69E+03	2.34E+04	**3.21E+04**	5.56E+05	1.52E+04	5.81E+08	**5.81E+08**
Fossil Fuel Consumption	MJ	6.20E+05	1.14E+04	**6.31E+05**	7.72E+03	2.34E+04	**3.11E+04**	5.28E+05	1.52E+04	4.66E+08	**4.66E+08**

END OF LIFE (C1 to C4)			BEYOND BUILDING LIFE (D)			TOTAL EFFECTS	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
2.05E+03	5.78E+02	**2.63E+03**	-2.83E+06	0.00E+00	**-2.83E+06**	**3.48E+07**	**3.19E+07**
1.88E+01	5.21E+00	**2.40E+01**	-1.29E+04	0.00E+00	**-1.29E+04**	**2.96E+05**	**2.83E+05**

1.01E+00	3.13E-01	**1.32E+00**	-1.10E+03	0.00E+00	**-1.10E+03**	**3.06E+04**	**2.95E+04**
1.05E+00	3.56E-01	**1.41E+00**	-2.94E+02	0.00E+00	**-2.94E+02**	**3.56E+03**	**3.27E+03**
1.34E-07	2.07E-08	**1.54E-07**	-2.71E-04	0.00E+00	**-2.71E-04**	**3.58E-03**	**3.31E-03**
5.47E+02	1.81E+02	**7.28E+02**	-1.21E+05	0.00E+00	**-1.21E+05**	**1.63E+06**	**1.51E+06**
2.87E+04	7.05E+03	**3.57E+04**	-3.62E+07	0.00E+00	**-3.62E+07**	**5.87E+08**	**5.51E+08**
2.86E+04	7.05E+03	**3.56E+04**	-3.58E+07	0.00E+00	**-3.58E+07**	**5.82E+08**	**5.46E+08**
2.78E+04	7.03E+03	**3.48E+04**	-3.42E+07	0.00E+00	**-3.42E+07**	**4.67E+08**	**4.33E+08**

Table A23 Bill of Materials Report (Precast Concrete Panel, Orlando, FL)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
1/2" Regular Gypsum Board	sf	4414.2997	0	0	0	0	4414.3	0	3.6436	Tons (short)
3 mil Polyethylene	sf	4256.9901	0	0	0	0	4256.99	0	0.0327	Tons (short)
Air Barrier	sf	4256.9901	0	0	0	0	4256.99	0	0.0266	Tons (short)
Aluminum Extrusion	Tons (short)	0.3434	0	0	0	0	0.3434	0	0.3434	Tons (short)
Aluminum Window Frame	lbs	5306.5462	0	0	0	0	5306.546	0	2.6533	Tons (short)
Double Glazed Soft Coated Air	sf	8860.6071	0	0	0	0	8860.607	0	14.6936	Tons (short)
Extruded Polystyrene	sf (1")	8347.03	0	0	0	0	8347.03	0	1.0514	Tons (short)
Galvanized Studs	Tons (short)	2.3419	0	0	0	0	2.3419	0	2.3419	Tons (short)
Glazing	Tons	0.6706	0	0	0	0	0.6706	0	0.6706	Tons

Panel	(short)									(short)
Joint Compound	Tons (short)	0.4512	0	0	0	0	0.4512	0	0.4512	Tons (short)
Nails	Tons (short)	0.0555	0	0	0	0	0.0555	0	0.0555	Tons (short)
Oriented Strand Board	msf (3/8")	5.6042	0	0	0	0	5.6042	0	3.4655	Tons (short)
Paper Tape	Tons (short)	0.0052	0	0	0	0	0.0052	0	0.0052	Tons (short)
Precast Insulated Panel	sf	4253.7797	0	0	0	0	4253.78	0	131.3834	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.026	0	0	0	0	0.026	0	0.026	Tons (short)
Water Based Latex Paint	Gallons (us)	139.8381	0	0	0	0	139.8381	0	0.4376	Tons (short)

Table A24 Detailed Summary Measure Table By Life Cycle Stages (Precast Concrete Panel, Orlando, FL)

		PRODUCT (A1 to A3)			**CONSTRUCTION PROCESS (A4 & A5)**			**USE (B2, B4 & B6)**			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	6.10E+04	6.12E+02	**6.17E+04**	6.10E+02	1.28E+03	**1.89E+03**	4.80E+04	1.20E+03	3.96E+07	**3.97E+07**
Acidification Potential	kg SO2 eq	3.72E+02	5.82E+00	**3.77E+02**	3.70E+00	1.25E+01	**1.62E+01**	3.65E+02	1.25E+01	3.28E+05	**3.28E+05**
HH Particulate	kg PM2.5 eq	6.39E+01	3.31E-01	**6.43E+01**	4.63E-01	7.14E-01	**1.18E+00**	4.96E+01	6.83E-01	2.65E+04	**2.66E+04**
Eutrophication Potential	kg N eq	1.10E+01	3.97E-01	**1.14E+01**	1.66E-01	8.51E-01	**1.02E+00**	9.53E+00	8.43E-01	3.50E+03	**3.51E+03**
Ozone Depletion Potential	kg CFC-11 eq	2.51E-03	2.26E-08	**2.51E-03**	3.32E-07	4.93E-08	**3.82E-07**	1.05E-03	4.86E-08	4.38E-05	**1.09E-03**
Smog Potential	kg O3 eq	3.67E+03	2.03E+02	**3.87E+03**	3.35E+01	4.35E+02	**4.69E+02**	2.51E+03	4.34E+02	1.25E+06	**1.25E+06**
Total Primary	MJ	7.02E+05	8.65E+03	**7.10E+05**	1.00E+04	1.66E+04	**2.66E+0**	5.68E+05	1.63E+04	6.57E+08	**6.57E+0**

Energy							**4**				**8**
Non-Renewable Energy	MJ	6.84E+05	8.64E+03	**6.92E+05**	9.23E+03	1.65E+04	**2.58E+04**	5.63E+05	1.63E+04	6.51E+08	**6.52E+08**
Fossil Fuel Consumption	MJ	6.54E+05	8.63E+03	**6.63E+05**	8.80E+03	1.65E+04	**2.53E+04**	5.40E+05	1.63E+04	6.19E+08	**6.20E+08**

END OF LIFE (C1 to C4)			**BEYOND BUILDING LIFE (D)**			**TOTAL EFFECTS**	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
2.06E+03	5.78E+02	**2.64E+03**	-2.83E+06	0.00E+00	**-2.83E+06**	**3.98E+07**	**3.69E+07**
1.89E+01	5.21E+00	**2.41E+01**	-1.29E+04	0.00E+00	**-1.29E+04**	**3.28E+05**	**3.16E+05**
1.00E+00	3.13E-01	**1.32E+00**	-1.10E+03	0.00E+00	**-1.10E+03**	**2.66E+04**	**2.55E+04**
1.05E+00	3.56E-01	**1.41E+00**	-2.94E+02	0.00E+00	**-2.94E+02**	**3.52E+03**	**3.23E+03**
1.34E-07	2.07E-08	**1.54E-07**	-2.71E-04	0.00E+00	**-2.71E-04**	**3.60E-03**	**3.33E-03**
5.46E+02	1.81E+02	**7.27E+02**	-1.21E+05	0.00E+00	**-1.21E+05**	**1.25E+06**	**1.13E+06**
2.88E+04	7.05E+03	**3.59E+04**	-3.62E+07	0.00E+00	**-3.62E+07**	**6.58E+08**	**6.22E+08**
2.87E+04	7.05E+03	**3.57E+04**	-3.58E+07	0.00E+00	**-3.58E+07**	**6.53E+08**	**6.17E+08**
2.81E+04	7.03E+03	**3.51E+04**	-3.42E+07	0.00E+00	**-3.42E+07**	**6.20E+08**	**5.86E+08**

Table A25 Bill of Materials Report (Precast Concrete Panel, Minneapolis, MN)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
1/2" Regular Gypsum Board	sf	4414.2997	0	0	0	0	4414.3	0	3.6436	Tons (short)
3 mil Polyethylene	sf	4256.9901	0	0	0	0	4256.99	0	0.0327	Tons (short)
Air Barrier	sf	4256.9901	0	0	0	0	4256.99	0	0.0266	Tons (short)
Aluminum Extrusion	Tons (short)	0.3434	0	0	0	0	0.3434	0	0.3434	Tons (short)
Aluminum Window Frame	lbs	5306.5462	0	0	0	0	5306.546	0	2.6533	Tons (short)
Double Glazed Soft Coated Air	sf	8860.6071	0	0	0	0	8860.607	0	14.6936	Tons (short)
Extruded Polystyrene	sf (1")	8347.03	0	0	0	0	8347.03	0	1.0514	Tons (short)
Galvanized Studs	Tons (short)	2.3419	0	0	0	0	2.3419	0	2.3419	Tons (short)
Glazing Panel	Tons (short)	0.6706	0	0	0	0	0.6706	0	0.6706	Tons (short)
Joint Compound	Tons (short)	0.4512	0	0	0	0	0.4512	0	0.4512	Tons (short)
Nails	Tons (short)	0.0555	0	0	0	0	0.0555	0	0.0555	Tons (short)
Oriented Strand Board	msf (3/8")	5.6042	0	0	0	0	5.6042	0	3.4655	Tons (short)
Paper Tape	Tons (short)	0.0052	0	0	0	0	0.0052	0	0.0052	Tons (short)
Precast Insulated Panel	sf	4253.7797	0	0	0	0	4253.78	0	131.3834	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.026	0	0	0	0	0.026	0	0.026	Tons (short)

Water Based Latex Paint	Gallons (us)	139.8381	0	0	0	0	139.8381	0	0.4376	Tons (short)

Table A26 Detailed Summary Measure Table By Life Cycle Stages (Precast Concrete Panel, Minneapolis, MN)

		PRODUCT (A1 to A3)			CONSTRUCTION PROCESS (A4 & A5)			USE (B2, B4 & B6)			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	5.95E+04	9.54E+02	**6.05E+04**	5.69E+02	1.57E+03	**2.13E+03**	4.68E+04	1.04E+03	3.40E+07	**3.40E+07**
Acidification Potential	kg SO2 eq	3.51E+02	9.80E+00	**3.61E+02**	3.15E+00	1.52E+01	**1.84E+01**	3.50E+02	1.07E+01	2.52E+05	**2.52E+05**
HH Particulate	kg PM2.5 eq	6.47E+01	5.36E-01	**6.52E+01**	4.88E-01	8.63E-01	**1.35E+00**	4.98E+01	5.90E-01	2.99E+04	**3.00E+04**
Eutrophication Potential	kg N eq	1.04E+01	6.64E-01	**1.11E+01**	1.51E-01	1.03E+00	**1.19E+00**	9.17E+00	7.24E-01	1.39E+03	**1.40E+03**
Ozone Depletion Potential	kg CFC-11 eq	2.51E-03	3.80E-08	**2.51E-03**	3.32E-07	5.95E-08	**3.92E-07**	1.05E-03	4.18E-08	2.58E-05	**1.07E-03**
Smog Potential	kg O3 eq	3.47E+03	3.41E+02	**3.81E+03**	2.81E+01	5.30E+02	**5.58E+02**	2.37E+03	3.72E+02	4.76E+05	**4.78E+05**
Total Primary Energy	MJ	6.74E+05	1.34E+04	**6.87E+05**	9.23E+03	2.08E+04	**3.00E+04**	5.49E+05	1.40E+04	5.48E+08	**5.49E+08**
Non-Renewable Energy	MJ	6.48E+05	1.34E+04	**6.62E+05**	8.25E+03	2.08E+04	**2.90E+04**	5.39E+05	1.40E+04	5.17E+08	**5.18E+08**
Fossil Fuel Consumption	MJ	6.08E+05	1.33E+04	**6.21E+05**	7.49E+03	2.07E+04	**2.82E+04**	5.10E+05	1.40E+04	4.38E+08	**4.39E+08**

END OF LIFE (C1 to C4)			BEYOND BUILDING LIFE (D)			TOTAL EFFECTS	
De-construction, Demolition, Disposal & Waste Proces	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**

sing							
2.05E+03	5.78E+02	**2.62E+03**	-2.83E+06	0.00E+00	**-2.83E+06**	**3.41E+07**	**3.12E+07**
1.88E+01	5.21E+00	**2.40E+01**	-1.29E+04	0.00E+00	**-1.29E+04**	**2.53E+05**	**2.40E+05**
1.01E+00	3.13E-01	**1.32E+00**	-1.10E+03	0.00E+00	**-1.10E+03**	**3.01E+04**	**2.90E+04**
1.05E+00	3.56E-01	**1.40E+00**	-2.94E+02	0.00E+00	**-2.94E+02**	**1.42E+03**	**1.12E+03**
1.34E-07	2.07E-08	**1.54E-07**	-2.71E-04	0.00E+00	**-2.71E-04**	**3.58E-03**	**3.31E-03**
5.45E+02	1.81E+02	**7.26E+02**	-1.21E+05	0.00E+00	**-1.21E+05**	**4.83E+05**	**3.63E+05**
2.86E+04	7.05E+03	**3.57E+04**	-3.62E+07	0.00E+00	**-3.62E+07**	**5.50E+08**	**5.14E+08**
2.84E+04	7.05E+03	**3.55E+04**	-3.58E+07	0.00E+00	**-3.58E+07**	**5.18E+08**	**4.82E+08**
2.77E+04	7.03E+03	**3.48E+04**	-3.42E+07	0.00E+00	**-3.42E+07**	**4.40E+08**	**4.05E+08**

Table A27 Bill of Materials Report (Precast Concrete Panel, Seattle, WA)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
1/2" Regular Gypsum Board	sf	4414.2997	0	0	0	0	4414.3	0	3.6436	Tons (short)
3 mil Polyethylene	sf	4256.9901	0	0	0	0	4256.99	0	0.0327	Tons (short)
Air Barrier	sf	4256.9901	0	0	0	0	4256.99	0	0.0266	Tons (short)
Aluminum Extrusion	Tons (short)	0.3434	0	0	0	0	0.3434	0	0.3434	Tons (short)
Aluminum Window Frame	lbs	5306.5462	0	0	0	0	5306.546	0	2.6533	Tons (short)
Double Glazed Soft Coated	sf	8860.6071	0	0	0	0	8860.607	0	14.6936	Tons (short)

Air										
Extruded Polystyrene	sf (1")	8347.03	0	0	0	0	8347.03	0	1.0514	Tons (short)
Galvanized Sheet	Tons (short)	1.1659	0	0	0	0	1.1659	0	1.1659	Tons (short)
Galvanized Studs	Tons (short)	2.3419	0	0	0	0	2.3419	0	2.3419	Tons (short)
Glazing Panel	Tons (short)	0.6706	0	0	0	0	0.6706	0	0.6706	Tons (short)
Joint Compound	Tons (short)	0.4512	0	0	0	0	0.4512	0	0.4512	Tons (short)
Nails	Tons (short)	0.0555	0	0	0	0	0.0555	0	0.0555	Tons (short)
Oriented Strand Board	msf (3/8")	5.6042	0	0	0	0	5.6042	0	3.4655	Tons (short)
Paper Tape	Tons (short)	0.0052	0	0	0	0	0.0052	0	0.0052	Tons (short)
Precast Insulated Panel	sf	4253.7797	0	0	0	0	4253.78	0	131.3834	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.026	0	0	0	0	0.026	0	0.026	Tons (short)
Water Based Latex Paint	Gallons (us)	139.8381	0	0	0	0	139.8381	0	0.4376	Tons (short)

Table A28 Detailed Summary Measure Table By Life Cycle Stages (Precast Concrete Panel, Seattle, WA)

		PRODUCT (A1 to A3)			**CONSTRUCTION PROCESS (A4 & A5)**			**USE (B2, B4 & B6)**			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	5.64E+04	8.43E+02	**5.72E+04**	4.54E+02	1.01E+03	**1.47E+03**	4.22E+04	1.11E+03	1.58E+07	**1.58E+07**
Acidification Potential	kg SO2 eq	3.07E+02	7.94E+00	**3.15E+02**	1.93E+00	1.05E+01	**1.24E+01**	2.97E+02	1.17E+01	7.59E+04	**7.62E+04**

HH Particulate	kg PM2.5 eq	6.20E+01	4.57E-01	**6.25E+01**	4.36E-01	5.50E-01	**9.86E-01**	4.26E+01	6.25E-01	5.88E+03	**5.93E+03**
Eutrophication Potential	kg N eq	1.05E+01	5.41E-01	**1.10E+01**	1.41E-01	7.11E-01	**8.52E-01**	9.00E+00	7.89E-01	6.52E+02	**6.62E+02**
Ozone Depletion Potential	kg CFC-11 eq	2.51E-03	3.10E-08	**2.51E-03**	2.02E-07	3.91E-08	**2.41E-07**	1.05E-03	4.48E-08	1.23E-05	**1.06E-03**
Smog Potential	kg O3 eq	3.62E+03	2.76E+02	**3.89E+03**	3.04E+01	3.66E+02	**3.97E+02**	2.29E+03	4.07E+02	1.72E+05	**1.74E+05**
Total Primary Energy	MJ	6.45E+05	1.14E+04	**6.56E+05**	8.16E+03	1.63E+04	**2.44E+04**	4.86E+05	1.61E+04	3.26E+08	**3.27E+08**
Non-Renewable Energy	MJ	5.85E+05	1.14E+04	**5.97E+05**	6.43E+03	1.63E+04	**2.27E+04**	4.38E+05	1.60E+04	1.79E+08	**1.79E+08**
Fossil Fuel Consumption	MJ	5.56E+05	1.14E+04	**5.68E+05**	6.02E+03	1.62E+04	**2.23E+04**	4.31E+05	1.60E+04	1.51E+08	**1.52E+08**

END OF LIFE (C1 to C4)			**BEYOND BUILDING LIFE (D)**			**TOTAL EFFECTS**	
De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
2.06E+03	5.78E+02	**2.64E+03**	-2.83E+06	0.00E+00	**-2.83E+06**	**1.59E+07**	**1.31E+07**
1.87E+01	5.21E+00	**2.40E+01**	-1.29E+04	0.00E+00	**-1.29E+04**	**7.66E+04**	**6.37E+04**
1.09E+00	3.13E-01	**1.40E+00**	-1.10E+03	0.00E+00	**-1.10E+03**	**5.99E+03**	**4.89E+03**
1.07E+00	3.56E-01	**1.42E+00**	-2.95E+02	0.00E+00	**-2.95E+02**	**6.75E+02**	**3.80E+02**
1.35E-07	2.07E-08	**1.56E-07**	-2.71E-04	0.00E+00	**-2.71E-04**	**3.57E-03**	**3.30E-03**
5.56E+02	1.81E+02	**7.37E+02**	-1.21E+05	0.00E+00	**-1.21E+05**	**1.79E+05**	**5.85E+04**
2.89E+04	7.05E+03	**3.60E+04**	-3.62E+07	0.00E+00	**-3.62E+07**	**3.28E+08**	**2.91E+08**
2.84E+04	7.05E+03	**3.54E+04**	-3.58E+07	0.00E+00	**-3.58E+07**	**1.80E+08**	**1.44E+08**
2.77E+04	7.03E+03	**3.48E+04**	-3.42E+	0.00E+00	**-3.42E**	**1.52E+08**	**1.18E+08**

			07		**+07**		

Table A29 Bill of Materials Report (Precast Concrete Panel, Los Angeles, CA)

Material	Unit	Total Quantity	Columns & Beams	Floors	Foundations	Roofs	Walls	Extra Basic Materials	Mass Value	Mass Unit
1/2" Regular Gypsum Board	sf	4414.2997	0	0	0	0	4414.3	0	3.6436	Tons (short)
3 mil Polyethylene	sf	4256.9901	0	0	0	0	4256.99	0	0.0327	Tons (short)
Air Barrier	sf	4256.9901	0	0	0	0	4256.99	0	0.0266	Tons (short)
Aluminum Extrusion	Tons (short)	0.3434	0	0	0	0	0.3434	0	0.3434	Tons (short)
Aluminum Window Frame	lbs	5306.5462	0	0	0	0	5306.546	0	2.6533	Tons (short)
Double Glazed Soft Coated Air	sf	8860.6071	0	0	0	0	8860.607	0	14.6936	Tons (short)
Extruded Polystyrene	sf (1")	8347.03	0	0	0	0	8347.03	0	1.0514	Tons (short)
Galvanized Sheet	Tons (short)	1.1659	0	0	0	0	1.1659	0	1.1659	Tons (short)
Galvanized Studs	Tons (short)	2.3419	0	0	0	0	2.3419	0	2.3419	Tons (short)
Glazing Panel	Tons (short)	0.6706	0	0	0	0	0.6706	0	0.6706	Tons (short)
Joint Compound	Tons (short)	0.4512	0	0	0	0	0.4512	0	0.4512	Tons (short)
Nails	Tons (short)	0.0555	0	0	0	0	0.0555	0	0.0555	Tons (short)
Oriented Strand Board	msf (3/8")	5.6042	0	0	0	0	5.6042	0	3.4655	Tons (short)
Paper Tape	Tons (short	0.0052	0	0	0	0	0.0052	0	0.0052	Tons (shor

	)									t)
Precast Insulated Panel	sf	4253.7797	0	0	0	0	4253.78	0	131.3834	Tons (short)
Screws Nuts & Bolts	Tons (short)	0.026	0	0	0	0	0.026	0	0.026	Tons (short)
Water Based Latex Paint	Gallons (us)	139.8381	0	0	0	0	139.8381	0	0.4376	Tons (short)

Table A30 Detailed Summary Measure Table By Life Cycle Stages (Precast Concrete Panel, Los Angeles, CA)

		PRODUCT (A1 to A3)			**CONSTRUCTION PROCESS (A4 & A5)**			**USE (B2, B4 & B6)**			
Summary Measure	**Unit**	Manufacturing	Transport	**Total**	Construction-Installation Process	Transport	**Total**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	6.08E+04	8.25E+02	**6.16E+04**	5.64E+02	4.23E+03	**4.80E+03**	4.61E+04	2.64E+03	3.01E+07	**3.01E+07**
Acidification Potential	kg SO2 eq	3.55E+02	7.73E+00	**3.62E+02**	3.06E+00	4.30E+01	**4.60E+01**	3.44E+02	2.75E+01	2.28E+05	**2.29E+05**
HH Particulate	kg PM2.5 eq	6.49E+01	4.47E-01	**6.53E+01**	4.67E-01	2.37E+00	**2.83E+00**	4.73E+01	1.50E+00	1.65E+04	**1.65E+04**
Eutrophication Potential	kg N eq	1.10E+01	5.27E-01	**1.15E+01**	1.57E-01	2.91E+00	**3.07E+00**	9.32E+00	1.86E+00	2.20E+03	**2.21E+03**
Ozone Depletion Potential	kg CFC-11 eq	2.51E-03	3.02E-08	**2.51E-03**	2.79E-07	1.67E-07	**4.46E-07**	1.05E-03	1.07E-07	6.15E-05	**1.11E-03**
Smog Potential	kg O3 eq	3.70E+03	2.69E+02	**3.97E+03**	3.17E+01	1.50E+03	**1.53E+03**	2.41E+03	9.58E+02	6.13E+05	**6.17E+05**
Total Primary Energy	MJ	7.09E+05	1.11E+04	**7.20E+05**	9.66E+03	5.85E+04	**6.81E+04**	5.47E+05	3.58E+04	5.55E+08	**5.55E+08**
Non-Renewable Energy	MJ	6.78E+05	1.11E+04	**6.89E+05**	8.56E+03	5.85E+04	**6.70E+04**	5.31E+05	3.58E+04	5.02E+08	**5.03E+08**
Fossil Fuel Consumption	MJ	6.44E+05	1.11E+04	**6.55E+05**	8.09E+03	5.83E+04	**6.64E+04**	5.12E+05	3.57E+04	4.74E+08	**4.74E+08**

END OF LIFE (C1 to C4)	**BEYOND BUILDING LIFE (D)**	**TOTAL EFFECTS**

De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**	BBL Material	BBL Transport	**Total**	**A to C**	**A to D**
2.10E+03	5.78E+02	**2.68E+03**	-2.83E+06	0.00E+00	**-2.83E+06**	**3.02E+07**	**2.74E+07**
1.92E+01	5.21E+00	**2.44E+01**	-1.29E+04	0.00E+00	**-1.29E+04**	**2.29E+05**	**2.16E+05**
1.12E+00	3.13E-01	**1.43E+00**	-1.10E+03	0.00E+00	**-1.10E+03**	**1.66E+04**	**1.55E+04**
1.07E+00	3.56E-01	**1.43E+00**	-2.95E+02	0.00E+00	**-2.95E+02**	**2.23E+03**	**1.93E+03**
1.35E-07	2.07E-08	**1.56E-07**	-2.71E-04	0.00E+00	**-2.71E-04**	**3.62E-03**	**3.35E-03**
5.57E+02	1.81E+02	**7.38E+02**	-1.21E+05	0.00E+00	**-1.21E+05**	**6.23E+05**	**5.02E+05**
2.96E+04	7.05E+03	**3.67E+04**	-3.62E+07	0.00E+00	**-3.62E+07**	**5.56E+08**	**5.20E+08**
2.93E+04	7.05E+03	**3.64E+04**	-3.58E+07	0.00E+00	**-3.58E+07**	**5.03E+08**	**4.68E+08**
2.87E+04	7.03E+03	**3.58E+04**	-3.42E+07	0.00E+00	**-3.42E+07**	**4.75E+08**	**4.41E+08**

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ACADEMIC VITA

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Bachelor of Science in Civil Engineering (Structures) anticipated May 2016
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WORK EXPERIENCE

Structural Engineer Intern, Arup, Beijing, China 6/15 – 7/15

- Reviewed CAD models, design drawings, and design reports of a 1,000-foot-tall high-rise building project.
- Utilized different computer software to analyze building models and data.
- Inspected several construction sites to assess the structural members installed.

Construction Engineer Intern, CITIC Group – Heye, Beijing, China 5/14 – 6/14

- Participated in Project China Zun, a 1,700-foot-tall high-rise building in Beijing, China.
- Collected information from the construction site to ensure progress and identify issues.
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ACTIVITIES

Member/Concrete Canoe Team Member, American Society of Civil Engineers (PSU Chapter) 9/14 – Present
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