University of Alberta

Carbon Footprint Assessment of the Pre-panelized Construction Process

by

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Abstract

Higher demand for residential construction in Canada in recent years has led some companies to move from conventional site-built construction to pre-fabrication methods. Although pre-fabrication can improve quality and construction speed, its sustainability in terms of CO_2 emissions compared to site-built construction also needs to be assessed. This research thus focuses on CO_2 assessment of the pre-panelized construction process in order to reduce the environmental impact of construction and provide a benchmark for the pre-panelized process. Results from the CO_2 assessment of a pre-panelized company process show that almost 40% of total CO_2 emissions are related to utility usage in the factory. Furthermore, a comparison of the carbon footprint of the company's current process to that of its past process (site-built framing) shows that pre-panelized wood framing leads to less CO_2 emissions per floor area if the company's production level exceeds a certain level.

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Chapter 1: Introduction

1.1 Motivation

According to the International Energy Agency, Canada's share of emissions due to fuel combustion in 2012 was 521 megatonnes (Mt), approximately 2% of global emissions. From 1990 to 2005, total emissions in Canada grew from 589 Mt to 740 Mt per year (Environment Canada, 2012a). Meanwhile, in 2007, over 50,000 residential units were built in Alberta, Canada and more than two million tonnes of carbon was released due to the operation phase of the construction life cycle. A previous study suggested that by using sustainable material this number could be reduced by 30% (Gonzalez and Navarro, 2005). In 2008, over 205,000 residential units were built in Canada, with 2,164,000 tonnes in associated CO_2 emissions (Statistics Canada, 2013 [Table 026-0001]; Statistics Canada, 2008b [Table 153-0034]). In 2009, over 540 million tons (490 million tonnes) of CO_2 were emitted to the air due to human activities in Canada (Statistics Canada, 2012). Most emissions were due to the burning of fossil fuels. Canada contributes 2% of the world's greenhouse gas (GHG) emissions, in spite of the fact that it has only 0.5% of the world's population (Statistics Canada, 2008b). In light of this fact it is incumbent upon Canada to make efforts to decrease its emissions. In this regard, in 2009 Canada signed the Copenhagen Accord and committed to lowering the level of its GHG emissions by 17% below the level of 2005 by 2020 (Environment Canada, 2012a). The extent of GHG emissions reduction would not be possible without the contribution of all industry sectors, including the construction industry.

Economic growth and higher demand for residential units have motivated residential construction companies in Alberta, Canada to adopt innovative methods of construction. Compared to conventional site-built construction, pre-fabrication methods such as pre-panelized and modular construction are faster in production. Pre-fabrication methods are also more convenient for cold climate regions due to the inherent difficulties of on-site construction in harsh weather conditions. Although pre-fabrication-based construction has many advantages in terms of production compared to traditional construction, it may not be sustainable in terms of CO_2 emissions. Devuyst (2011) defined sustainability as "a tool that can help decision-makers and policy makers decide what actions they should take and should not take in an attempt to make society more sustainable." The term "sustainable construction" in the context of this research refers to the application of construction processes, which are energy- and resource-efficient. In this regard, as Siddiqi et al. (2008) have argued, "sustainable construction provides many advantages, including the efficient use of resources, cost savings and enhances quality of life" (Siddiqi et al., 2008).

Effective energy utilization and process improvement are the primary challenges facing pre-fabrication construction companies. Energy utilization and process improvement lead to higher profit levels and can help construction companies to be more sustainable. Carbon dioxide (CO_2) is a common by-product of industrial sectors resulting from energy consumption (Stolarski et al., 2006). In this study, carbon assessment is recommended as a tool to assist pre-fabrication-based construction companies in decision making to ensure efficient energy utilization and sustainability.

1.2 Research objectives

The hypothesis underlying this research is that:

"Accurate carbon footprint measurement of the pre-panelized construction method enables panel manufacturers to reduce the environmental impact of their process as well as energy consumption, which could lead to significant cost savings."

Based on this hypothesis, the objectives of this research are to

1) Quantify the direct CO_2 emissions of the pre-panelized process
2) Provide a benchmark for carbon footprint of the process (average monthly CO_2 emissions)
3) Provide suggestions to improve pre-panelized process sustainability (in terms of CO_2 emissions)
4) Compare energy consumption (by means of CO_2 assessment) and material waste (pre-panelized vs. stick-built)
5) Model and simulate the CO_2 emissions of the pre-panelized process

1.3 Organization of the Thesis

This thesis comprises five chapters. Chapter One commences with a description of the motivations for conducting this research. The objectives of the study are then explained and the thesis structure is outlined. Chapter Two provides a literature review of previous studies related to GHG emissions and applicable methods of assessment. Chapter Three outlines the research methodology and data collection framework for achieving the objectives of the research. Chapter Four presents the developed framework, simulation model, and final results. It also explains the implementation steps in a case study. Chapter Five summarizes the conclusions and direction for future research.

Chapter 2: Literature Review

2.1 Introduction

This chapter reviews the existing literature related to life cycle assessment (LCA), the necessity of greenhouse gas (GHG) emissions reduction, the effect of building materials on CO_2 emissions and energy consumption, and the concept of sustainable building.

2.2 Literature review related to the necessity of GHG emissions reduction

In a greenhouse, the sun's radiation passes through the glass and is absorbed by plants and soil. Most of this energy ultimately converts to heat which warms up the greenhouse. The glass effectively traps the heat inside the greenhouse and helps to keep the air warm. The earth's atmosphere, analogously, functions like the glass in a greenhouse (Schneider, 1989; The Greenhouse Effect, 2012). Greenhouse gases refers to several gases in the atmosphere such as carbon dioxide (CO_2), methane (CH_4), and ozone (O_3), which increase the earth's temperature by absorbing and trapping the sun's solar radiation. Of these gases, CO_2 is the major and most important by-product of human activities. In the past years, human activities have increased the level of CO_2 in the atmosphere (Buchanan and Honey, 1994). Studies show a direct relationship between human activities and the level of CO_2 emission. Based on previous studies the concentration of CO_2 in the atmosphere is significantly higher than other greenhouse gases. Thus, CO_2 has more contribution to the global warming phenomenon than other greenhouse gases (Dickinson and Cicerone, 1986) (Stolarski et al., 2006). Studies show that "about 31% of the incoming radiation from the sun is reflected directly back to space by the earth's atmosphere and surface (particularly by snow and ice). Another 20% is absorbed by the atmosphere. The rest of the incoming radiation is absorbed by the earth's oceans and land, where it is converted into heat, warming the surface of the earth and the air above it" (The Greenhouse Effect, 2012). In the phenomenon known as the greenhouse effect, GHGs in the atmosphere such as CO_2 absorb heat from the sun and radiate it to the earth's surface. Without GHGs in the atmosphere, the earth's temperature would be about 33°C colder than what it is now. Thus greenhouse effect has significant impact on the earth temperature.

Sustainable temperature, meanwhile, has a positive impact on the water cycle, which is necessary for supporting life on earth. Thus, if the level of GHGs in the atmosphere exceeds the normal level, it could have a negative impact on the environment. For example, incremental increases in global temperature will melt ice polar caps and raise sea levels, therefore putting coastal areas in a greater risk of flooding (The Greenhouse Effect, 2012). "One of the greatest concerns associated with climate change is the anticipated increase in the frequency of extreme weather events. The ice storm that struck eastern Canada in 1998 illustrates the magnitude of the potential impact of these events" (Statistics Canada, 2008b). The other concern, regarding temperature increase, is building and maintaining ice roads in northern communities (Statistics Canada, 2008b).

Scientists spent decades in search of the causes of global warming, and initially they traced the pattern to naturally-occurring gases in the atmosphere (Causes of Global Warming, 2013; Dator, 2010). More recently, many scientists have identified a direct relationship between the level of CO_2 in the atmosphere and global temperature, and have drawn attention to the impact of human activities on the planet's CO_2 levels and climate change. In 1938, G.S. Callendar announced that the level of CO_2 in the atmosphere had risen, but still at that time only a few scientists believed that global warming was possible and should be considered as a serious issue (The Carbon Dioxide Greenhouse Effect, 2011). According to a study by Soon (1999), the level of CO_2 increased significantly between 1960 and 2000. Scientists believed that the rise in CO_2 level was due to human activities, and their thinking was supported by the observed correlation between the magnitude of CO_2 released due to human activities and the rise of CO_2 levels in the atmosphere (Soon, 1999). Also another study shows a consistent relationship between human activities and the level of GHG emission. In that study, it is noted that "overall, emissions in 2010 in Canada were 692 mega tons. This is a 0.25% increase over 2009 levels" (Environment Canada, 2012b). This includes all GHGs for all sectors.

Studies related to CO_2 emissions in recent decades suggest that CO_2 emissions and energy consumption should be major concerns in industrial sectors. These concerns are particularly pressing with respect to large-scale industry due to the higher fossil fuel and energy consumption. Large industrial companies can produce tons of carbon emissions. Previous studies have highlighted this fact by giving examples of emission levels and energy consumption for various industrial sectors and jurisdictions. For instance, according to Acquaye and Duffy (2010), the construction sector in Ireland was responsible for the emission of 13.81

mtCO_2eq (megatons equivalent carbon dioxide) in 2005. Another study in Japan showed that the housing construction sector consumed 416,000 TJ (TeraJoule) of energy in 1994 (Suzuki et al., 1994). In 2001, the U.S. residential sector in construction phase was responsible for approximately 18.6 EJ (EJ=10 TJ) of energy and 1.155 gigatons (Gt) of carbon (Upton, 2008). In this regard, Gonzalez and Navarro (2005) noted that the production of a conventional home releases approximately 45 tons of CO_2 into the atmosphere. In Alberta alone during 2007, the construction of approximately 50,000 residential units resulted in the release of more than two million tons of CO_2 (Mah, 2011). According to some estimates the operation phase of building construction accounts for 40% of nations' GHG emissions (Dator, 2010).

Such results have motivated many countries to make efforts to reduce the level of their GHG emissions, including by entering into international agreements such as the Kyoto Protocol (Hayami and Nakamura, 2007). Canada as a country with a large industrial sector has a particularly pressing responsibility to reduce its GHG levels. According to the Kyoto Protocol, Canada was required to reduce its CO_2 emission level in the period of 2008-2012 by 6% from the level in 1990, which would have necessitated a reduction of CO_2 emissions by 240 million tons per year by 2010 (Hayami and Nakamura, 2007). A more recent study has noted that Canada by signing the Copenhagen Accord committed to reducing the level of its GHG emissions by 17% below the level of 2005 by 2020 (Environment Canada, 2012a). As a result of efforts to reduce GHG emissions, the top ten energy-consuming industries in Canada have shown a decline in their energy consumption. Electric power generation, transmission, and distribution sectors as the largest industries in Canada reduced their intensity index by 2.9% between 2007 and 2008 (Statistics Canada, 2012a). Although this a positive sign in terms of reducing the level of GHG emissions in Canada, efforts to reduce emissions should not be attenuated.

Although GHG assessment leads to a more sustainable process in terms of energy consumption for industrial sectors, there are concerns regarding GHG assessment that have to be considered. A study by Berners-Lee et al. (2011) identified GHG emissions reduction as a crucial factor affecting the reputations of businesses, although businesses are usually unwilling to pursue emissions reduction if it is not financially justified. In other words, if assessment and strategies for GHG emissions mitigation provide solutions that reduce costs, then companies will contribute more to this area. Focusing on the cost reduction of different emissions is the key to implementing change in terms of the environmental impact of industrial activity (Berners-Lee et al., 2011).

2.3 Literature review related to life cycle assessment approach

One of the concerns in CO_2 assessment is the accuracy of the evaluation method. Among the different methods, LCA is popular but it suffers as a result of a truncation issue. In other words, in order to simplify the process of assessment, some part of the process may be omitted. Input-output analysis (IOA) is an effective method, which effectively addresses the truncation issue, but it involves an aggregation problem. Hybrid models that combine LCA and IOA together lead to fewer errors. Berners-Lee et al. (2011) have provided an algorithm based on the hybrid model, which exploits the benefits of both LCA and IOA in order to analyze GHG emissions of construction trades. Berners-Lee et al. (2011) applied a hybrid model within the tourism sector to evaluate the monetary value of energy corresponding to GHG emissions. By applying the hybrid model in that study, they found that electricity production and distribution sector has the highest contribution in the tourism industry in terms of GHG emissions (Berners-Lee et al., 2011). Although hybrid methods are more accurate, the LCA method is simpler and more popular in GHG assessment.

As Svoboda has advanced, “LCA has its roots in the 1960s, when scientists concerned about the rapid depletion of fossil fuels developed it as an approach to understanding the impacts of energy consumption” (Svoboda, 1995). Svoboda has defined LCA as a systematic approach to evaluate the environmental consequences of producing a certain product from cradle to grave. Svoboda applied LCA to analyze a system; in that study raw materials, energy, and water were considered as inputs, while emissions into the air, releases into water, solid waste, usable products, and other environmental releases were considered as outputs (Svoboda, 1995). Urie (2004) defined LCA as a system which identifies and quantifies the inputs (e.g., materials and energy) and outputs (e.g., emissions into the air). Elcock (2007) defined the life cycle as a concept that “is based on the premise that products and processes have life cycles. Products are made from raw materials, transported, used, and eventually disposed of” (Elcock, 2007).

Hundal (2001) has defined three steps for the process of LCA: inventory analysis, impact analysis, and improvement analysis. Inventory analysis includes the process of data collection for raw materials, energy consumption in a certain process, solid waste, and other data factors that can affect CO_2 emissions and embodied energy. Impact analysis determines the effect of environmental issues due to the inventory factors. Improvement analysis aims to identify methods and opportunities to reduce the environmental impacts of the last two steps, and this step could be qualitative, quantitative, or both (Hundal, 2001). A study by Urie and Dagg (2004) divided LCA into six different stages: extraction of raw material, manufacturing, distribution, construction, building use, and demolition (disposal and/or recycling). A study by Elcock (2007) has offered a slightly different breakdown of stages for LCA: extraction of raw material, processing, manufacturing, transportation, distribution, using or reusing, and recycling and waste management. Elcock has also described four steps for the LCA process. The first step is to define the goals and scope, the objectives of which include "gaining a better understanding of an existing system, identifying the main environmental problems in the product or process life cycle, identifying opportunities for improving the existing system, comparing systems and their potential impacts, and selecting options prospectively" (Elcock, 2007). The second step, life cycle inventory (LCI), involves collecting data to satisfy the defined goals and scope of the system. The third step, life cycle impact assessment (LCIA), is carried out to "provide information to understand and assess the magnitude and significance of the potential environmental impacts associated with the inventory results" (Elcock, 2007). The final step, life cycle interpretation, is a systematic approach to present solutions in line with the defined scope. According to ISO 14041, a comprehensive LCA includes three phases, which may be defined as (1) life cycle inventory analysis, (2) life cycle impact assessment, and (3) life cycle interpretation (ISO 14041, 1998).

LCA as a practical tool for the assessment of environmental impacts of firm activities can potentially provide useful feedback for policy makers, assisting them in utilizing their resources in such a way as to have less impact on the environment (Elcock, 2007). However, although LCA is a practical tool for CO_2 assessment, there are concerns to be considered. In particular, one of the concerns that could be considered in LCA is the size of study targets. Most large companies will consider enlisting the services of an expert entity from outside to conduct the CO_2 assessment, but justifying LCA for small companies may be a problem. Another concern has to do with the data collection stage of the LCA process. Data collection is an important part of LCA, and poor data collection leads to errors in the validation of the system and results (Elcock, 2007).

CO_2 emissions assessment for a process or a product needs to be carried out by applying relevant emission factors. Hammond and Jones (2008) conducted a study developing an open-access, reliable database for embodied energy and CO_2 emissions associated with the construction industry. They described embodied energy as “the quantity of energy required to process, and supply to the construction site, the material under consideration” (Hammond and Jones, 2008). On the basis of this definition, they traced the flow of energy through the relevant industrial sector. In an inventory developed by researchers at the University of Bath (U.K.), a flowchart has been developed to refine the results in a repetitive process. Some of the variations that exist in the inventory are related to system boundaries. The term "system boundary" refers to factors such as geographical region that have an impact on values (Hammond and Jones, 2008). In general, the inventory has a wide range of elements and materials that can be used for calculating CO_2 emissions and embodied energy.

LCA can be effectively applied for CO_2 and energy assessment in various companies and sectors, but only limited research has been conducted regarding the direct relationship between construction methods and GHG emissions. Most studies have compared the CO_2 emissions of buildings in terms of various materials and functionality, but very few of them have focused on construction methods. Mah (2011) has focused on the CO_2 emissions intensity of residential units built using the stick-built method. In this research, CO_2 assessment for the construction process was conducted by applying LCA. The construction process in this research was divided into 17 evaluative stages, and the results showed that the drywall taping and texture stage of construction emits more CO_2 than other specified stages. Mah then proposed a methodology for quantifying CO_2 emissions by applying building information modelling (BIM) tools and techniques, and validated the results in a case study (Mah, 2011).

LCA, it should be noted, is not limited to the construction of buildings. For example, LCA can be effectively applied to road construction. Large quantities of various recycled secondary materials and aggregates in are used in road construction, such that LCA can serve to reduce the demand for excavation and landfill (Huang, 2009). Previous studies have shown, for instance, that using recycled glass as a road construction aggregate produces more CO_2 emissions than sending the same material to the landfill (Dacombe, 2004; WRAP, 2006). A study by Huang (2009) has developed an LCA model for paving asphalt which aimed to increase speed, quality, and communication. In terms of the application of LCA for a product, Boguski (2010) has evaluated the life cycle carbon footprint of *National Geographic* magazines. The stated objective of this study was to provide information for suppliers for the purpose of reducing the life cycle GHG emissions of magazines (Boguski, 2010).

2.4 Literature review related to the effect of building materials on CO_2 emissions and energy consumption

LCA helps in selecting reasonable materials and technologies for buildings based on consideration of both short- and long-term environmental impacts (Zabalza et al., 2011). In this respect, a study by Buchanan and Honey (1994) has shown that selection of building materials should not be based only on the owner's requirements, but should consider "the effects of extraction, manufacture and processing of building material on the social and natural environment of this planet" (Buchanan and Honey, 1994). Buchanan and Honey in this New Zealand study focused on the CO_2 emissions comparison between different types of buildings, such as hustles, residential, industrial, and office facilities. In their study, application of different materials for the structure of each building showed significant differences in the amount of CO_2 emitted. The results showed that constructing an office building using steel structure produces more CO_2 than using other materials. Their comparison between different stages of residential construction also revealed that constructing concrete slab in the floor stage produces more carbon than other stages. Buchanan and Honey (1994) concluded that the utilization of renewable resources such as wood in buildings can reduce the amount of CO_2 emitted, but that forestry issues may arise from using wood as the primary material in construction.

A study in Japan by Suzuki et al. (1994) has focused on the quantification of energy and cost related to different stages of the residential construction process by applying LCA. These findings suggest that CO_2 quantification through LCA can effectively facilitate GHG reduction. Suzuki et al. considered various domestic goods and services in a LCA to quantify the magnitude of embodied energy and CO_2 emissions. In that study, the process of constructing a house was divided into smaller sub-categories such as temporary work, structure work, finishing work, equipment work, and general management work. The cost for each section was categorized further into material costs and labour costs. Quantification of resources and analysis of different types of houses, including multi-family, single-family wood-framed, and light-weight houses, showed that multi-family houses consume more energy and produce more CO_2 per house than other types. Suzuki et al. concluded that a wood-framed house has less impact on the environment in terms of CO_2 emissions than types of houses built with other materials (Suzuki et al., 1994).

Börjesson and Gustavsson (2000) have concluded that compared to using wood, concrete for the frame of a house produces 60-80% higher amounts of CO_2. Fossdal (1995) has shown that the amount of carbon which is deposited in wood may be considered as a positive number which can be further added to the operation CO_2 emissions of lumber production, which may be considered as a negative number in CO_2 assessment. On the other hand, for the assessment of CO_2 emissions of concrete-framed houses, CO_2 emissions due to process of producing cement must be included. Fossdal thus concluded that, compared to lumber, the CO_2 emissions associated with concrete as a building material are higher.

Several studies have demonstrated, by considering the energy and carbon factors associated with the U.S. construction industry, that embodied energy and CO_2 emissions for the construction of a conventional house in the United States is approximately one-tenth of the carbon and energy consumption that is used for heating and cooling homes (Lippke, 2004; Peirquet, 1988; Marceau and Van Geem, 2002). Given this fact, selection of proper building materials becomes more important in reducing CO_2 emissions due to the energy consumption in the operation of buildings. Upton (2008) has compared energy and CO_2 emissions of wood-based homes with non-wood-based homes throughout the home's life cycle (based on 100 years of occupancy). Upton has found that "houses built with wood-based systems required about 15-16% less total energy for non-heating/cooling purposes than thermally comparable houses employing alternative steel- or concrete-based building systems" (Upton, 2008). In the same study, Upton has reported that "net GHG emissions associated with wood-based houses were 20-50% lower than those associated with thermally comparable houses employing steel- or concrete-based building systems" (Upton, 2008). Marceau and Van Geem (2002) have focused on the effect of building materials on household energy consumption by applying an LCA approach. In that study, houses with masonry unit exterior walls were compared to houses with wooden exterior walls. The boundary for conducting the LCA was defined as the interface between a product system and the environment. Study targets were located in five different regions of the United States in order to better represent the range of climatic conditions in the country. Final results demonstrated that, in colder climates, houses with masonry unit exterior walls show lower energy consumption. In warmer climates, on the other hand, the impact indicator for houses with masonry unit exterior walls was greater due to higher household energy usage. The results showed that most of the household energy consumption was due to electricity and natural gas usage (Marceau and Van Geem, 2002).

Based on literature reviews, using wood as a renewable material and a source of energy (fuel) leads to reduced CO_2 emissions during the life cycle of buildings. In other words, replacing infinite natural resources such as wood with finite resources such as fossil fuels for construction materials minimizes the effect of materials on the environment (Zabalza et al., 2011). It should also be considered that trees as the source of wood products absorb CO_2 in the process of photosynthesis. Fischlin (1996) has shown that long-living wood products contribute to GHG mitigation in a number of ways. For instance, a tree withdraws carbon from the atmosphere during its natural life (Fischlin, 1996); wood acts as a carbon pool during its service life; and wood products can be used as a replacement for fossil fuels after their service life, which leads to reduced usage of fossil fuels (Werner, 2006). However, although increased usage of wood as a building material and as a source of fuel after its service life serves to reduce carbon emissions in some ways, there are concerns regarding the overall amount of CO_2 emitted in the production of wood products. The study by Börjesson and Gustavsson (2000) has shown that for the production of 1 m^3 of rough timber, 2 m^3 of stem wood are needed. As trees are cut for lumber, much of the branches and tree tops remain as residue. According to another study, 25% of the biomass produced by stem wood is due to residue of branches and tree tops (Börjesson et al., 1997). Thus, for the production of a wooden house, an additional amount of carbon from the residual materials of harvested trees must be accounted for as well.

Material waste in industrial firms such as construction companies is another environmental concern that must be properly managed. According to one study, in the construction or renovation of new buildings in Alberta, Canada, around 22% of the required building materials—which may include wood, steel, concrete, or other building debris—will be wasted (C & D Waste Reduction Advisory, 2006). The fact that waste from the construction process contributes significantly to pollution makes waste management particularly critical (Craven, 1994). Shen (2004) has demonstrated that, while in the short term waste management, due to the associated costs for staffing, new technologies, and facilities, increases the cost of construction, by mapping waste flow, waste management leads to cost savings in the long term. As this study has advanced, managing the waste in construction is strongly dependent site management, where a proper approach to site management can serve to reduce waste markedly (Shen et al., 2004). Edwards (1999) has introduced recycling as a positive approach in waste reduction. Tam et al. (2009) in this regard has indicated that recycling, by reducing the demand for virgin materials, can help to preserve natural resources. Recycling, by reducing the demand for the transportation of waste to landfills, also makes the process of construction more energy efficient (Tam et al., 2009).

Construction method is another factor that affects waste reduction. A study by Jaillon, et al. (2009) has analyzed the issue of waste in Hong Kong's construction industry. According to that study, prefabrication as a sustainable method recommended by the government of Hong Kong leads to waste reduction. Pre-fabrication in populated cities with high building density such as Hong Kong could reduce onsite waste. The study has shown that standardization of construction processes improves waste management by providing a framework conducive to waste reduction. Jaillon's research has shown that prefabrication as a construction method makes waste more controllable than do conventional construction methods (Jaillon et al., 2009).

2.5 Literature review related to the concept of sustainable building

The concept of green building emerged out of concerns about energy and natural resources. The aim of this concept is to minimize the impacts of buildings on the environment. In this regard, Kibert (2008) has purported that "sustainable construction is a subset of sustainable development and addresses the role of the built environment in contributing to the overarching vision of sustainability." Dator (2010) in this regard has noted that "sustainable building or high performance building—is generally referred to as the practice of increasing building efficiency, and protecting and restoring human health and/or the environment." At this point rating programs may be considered as guidelines that aid in optimizing sustainability. Mora (2007) in a previous study has suggested that green construction can refer to both the building process and to built objects. In this regard, Bronin (2008) has stated that "Evidence indicates that buildings contribute to increased CO_2 emissions and energy inefficiency because of construction methods and buildings' subsequent energy practices"

Sustainable building rating systems may encompass an examination of the performance or the expected performance of buildings. Without rating programs, the concept of sustainability will be more qualitative rather than quantitative. Given this fact, Gowri (2004) has categorized green building rating programs into five sections with respect to the design and life cycle of a building: (1) site, (2) water, (3) energy, (4) materials, and (5) indoor environment. For each section of the rating system, credits are assigned which specify the degree of suitability of the building. In order to add value to the sustainability of a building, various criteria with respect to its life cycle have to be met. Based on the necessary conditions for assigning credit to the sustainability of a building, a number of different rating systems have been developed, including Building Research Establishment's Environmental Assessment Method (BREEAM), Comprehensive Assessment System for Building Environmental Efficiency (CASBEE), GBTool, Green Globes, and Leadership in Energy and Environmental Design (LEED) (Fowlerand and Rauch, 2006).

The practice of green building is not only limited to conventional buildings, but can also apply to urban development programs (Sinha, 2009).

Although urban growth leads to overall increased GHG emissions, tall buildings and high-rises can be more efficient than low-rise buildings in terms of GHG emissions. Because tall buildings are constructed upwards, the general per unit footprint is less than with outward urban development in terms of the land occupied. Also, due to the sharing of resources such as utilities, walls and floors in tall buildings, this type of urbanization can be considered more efficient and sustainable (Dator, 2010).

2.6 Chapter summary

Relatively few research studies have directly addressed the issue of the environmental impact of construction method. Most previous studies have focused on the impact of construction materials on the CO_2 footprint of construction. In order to fill this gap in the literature, construction method as a relevant factor affecting CO_2 emissions assessment is the primary focus of this research.

Chapter 3: Research Methodology

3.1 Introduction

The term "carbon footprint assessment", used in this research, refers to direct or indirect CO_2 emissions which accumulate as the result of different activities within a portion of a product's life cycle (wood framing stage). All activities which contribute to CO_2 emissions within a portion of a pre-panelized house's life cycle are encompassed by the assessment. The evaluation captures the impacts within the defined product life cycle in an approach which can be considered life cycle assessment (LCA).

Direct emissions refer to CO_2 emitted in the operation stage of the product life cycle. Fossil fuels used in any form in the operation stage contribute to direct emissions. Other sources of energy which are produced from fossil fuels, such as electricity, also contribute to direct emissions. "Indirect emissions" refers to CO_2 emitted due to raw material consumption and the associated waste. The main difference between the on-site stick-built and pre-panelized house life cycles in terms of carbon footprint is during the wood framing process. All the other stages before and after wood framing are the same for both methods. Thus, carbon footprint assessment in this research is limited to the framing stage of a wood-framed home's life cycle. The cradle-to-grave life cycle of a pre-panelized wood-framed home includes (1) extracting the wood, (2) transporting the wood to the lumber factory, (3) manufacturing the lumber, (4) transporting the lumber to the pre-panelized factory, (5) manufacturing the panels, (6) transporting the panels to the field, (7) assembling the panels, (8) maintenance, and (9) demolition. Figure 1 depicts the scope of this study, which spans the steps 4 through 7.

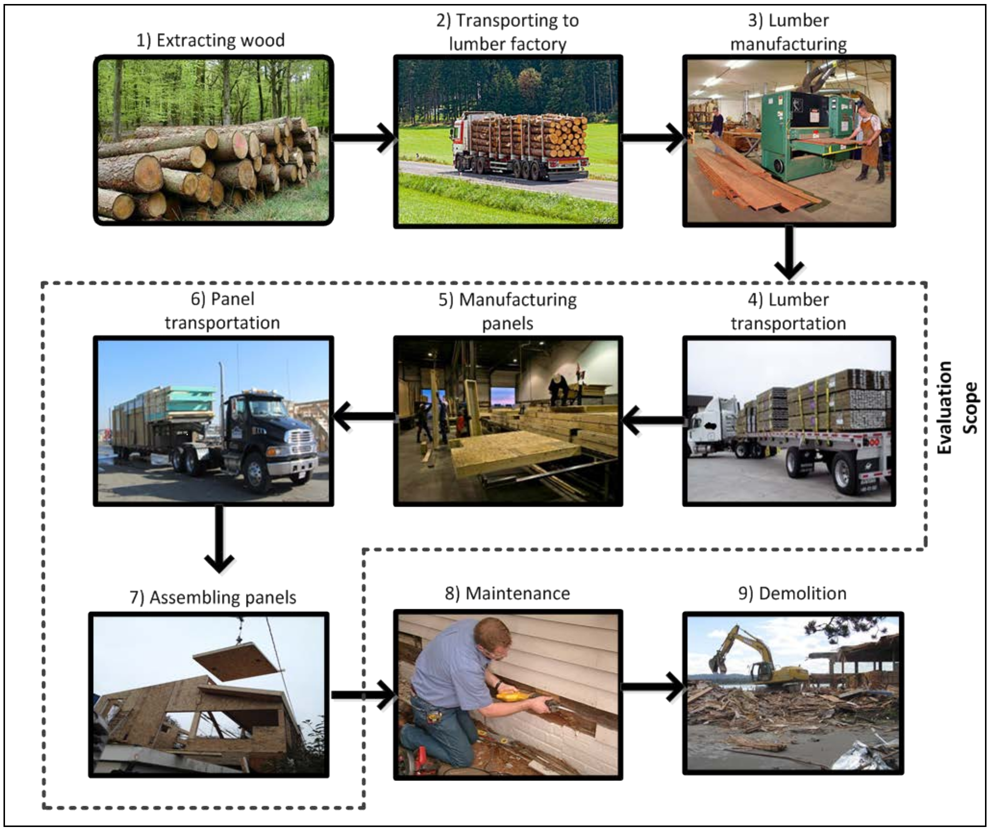

Figure 1 Pre-panelized house life cycle

3.2 Research method

The research methodology framework comprises four parts: (1) inputs, (2) criteria, (3) process, and (4) outputs. Fossil fuel consumption in any form within the wood framing stage is related to energy components. Diesel, gasoline, propane, electricity, and natural gas records are thus required inputs within the research framework. Wood waste records are the other framework inputs which are used in indirect CO_2 emission assessment. Emission factors represent the geographical and technological aspects of a particular area. The term “emission factors” in this research refers to “representative values relating the quantity of an emission with an activity associated with the release of that emission" (Environment Canada, 2010). The applicable emission factors for this research pertain exclusively to Canada's construction sector. Table 1 presents the emission factors for related energy components (Environment Canada, 2011a; 2011b).

Table 1: Canadian emission factors

Energy Component	**Emission factor**
Natural gas (kg/m3)	1.918
Electricity (kg/kWh)	0.83
Gasoline (kg/litre)	2.289
Diesel (kg/litre)	2.663
Propane (kg/litre)	1.51

There are four evaluative stages in the operation process of pre-panelized wood framing: (1) delivery stage, (2) manufacturing stage, (3) transportation stage, and (4) erection stage. Activities taking place outside these four stages are beyond the scope of this study. Furthermore, although some activities fall within the defined scope, their duration may extend beyond the wood framing stage. For example, winter heating (heating the basements on site in winter) is an activity in the assembling stage of framing, but heaters may be kept running after wood framing is complete. Accordingly, only a portion of the duration and the associated CO_2 emissions is considered for such activities. The process of this research begins with data collection. Relevant emission factors for each energy component must be retrieved from reliable inventories which are consistent with the region of study as well. In general, CO_2 emission calculation for each activity is carried out using the following equation.

$$\text{Activity } CO_2 \text{ emissions } = \text{Energy Component Quantity } \times \text{Emission Factor}$$

(Equation 1)

Developing a simulation model which quantifies the benchmark of the pre-panelized process in the long term based on a historical data is specified as the third step in the framework process. The pre-panelized process benchmark in this step is the result of average CO_2 emissions of the pre-panelized process over several years.

In order to compare the carbon footprints of stick-built and pre-panelized construction methods, stick-built results are modified to accommodate the pre-panelized study boundaries. The final results and charts will help pre-panelized construction companies to improve the sustainability of their process. The monthly charts demonstrate seasonal CO_2 and energy use variations. The comparison results can also specify the minimum annual production of the pre-panelized factory needed to maintain the sustainability of the overall process for a particular year. In other words, the pre-panelized method will ensure fewer CO_2 emissions per unit if the company's production exceeds a certain level. A pre-panelized carbon footprint benchmark, average emission baselines, and simulation of CO_2 emissions are the other outputs of this research. Figure 2 illustrates the research framework.

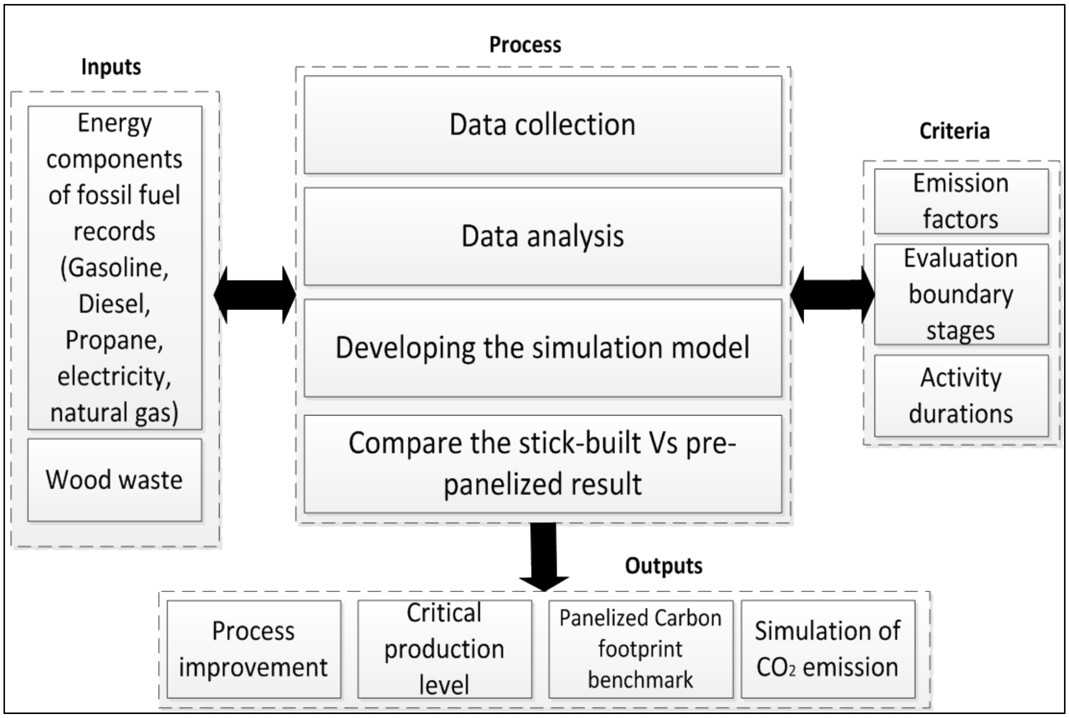

Figure 2 Research methodology

3.3 Data collection

This research is an empirical study based on collected data from the operations of Landmark Building Solutions (LBS), which is the pre-panelized factory of Landmark Group of Builders, a major home builder operating in Alberta, Canada. Based on availability, the data is collected from two sources:

1) Historical data records were considered as the most reliable data source. Utility usage of the manufacturing facility (i.e., electricity, natural gas); propane usage in the facility; and diesel consumption of the LBS fleet, including cranes, semi-trailers, and garbage trucks were collected directly from accounting records. Information related to the commuting mode of the employees, total number of employees, and average travel distance have been provided for this research in the form of a spreadsheet by the

company. The company, which provided the data required for the study, collected the data in 2012 as standard practice in the form of aggregated, anonymous data.

2) Transporting of raw materials (i.e., lumber, engineered wood, and window/doors) is tracked based on operation hours. The data has been collected from accounting records, while the hourly fuel consumption is estimated based on observations and verified using theoretical formulae from the user manuals of the fleet's vehicles.

Table 2 summarizes activities, associated energy components, and data collection resources, and Figure 3 presents the developed framework for data collection. Theoretical formulae from the user manuals of the fleet's vehicles are applied to verify the estimated fuel consumptions.

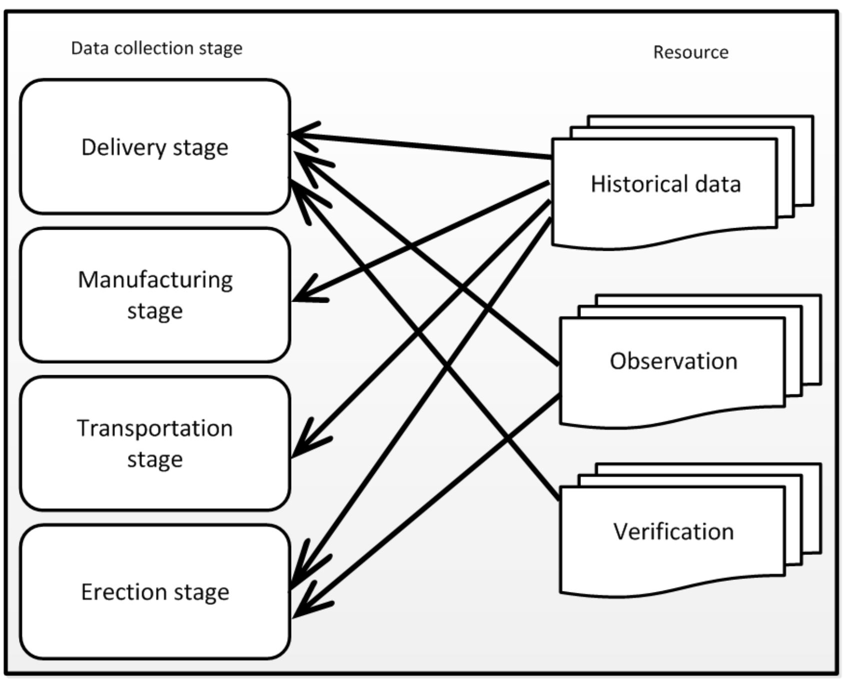

Figure 3 Data collection framework

Table 2: Data collection framework

Stage	Section	Element of CO_2 emission	Data collection	Notes
1. Delivery stage	1.1 Lumber delivery fuel consumptions	Diesel	Observation + Historical data (bills) + verification	Trucks start their trip from rental company to the supplier company to load lumbers and deliver to LBS
	1.2 Doors and windows delivery fuel consumptions	Diesel	Observation + verification	A dry van pull trailers once a day
2. Manufacturing stage	2.1 Electricity and natural gas usage	Electricity & Natural gas	Historical data (bills)	Electricity is based on kWh and natural gas is based on GJ
	2.2 Plant machinery fuel consumptions	Propane	Historical data (bills)	Based on lbs (needs to be converted to Litre)
	2.3 Plant workers fuel consumptions	Gasoline & Diesel	Historical data	54 plant workers
	2.4 Office workers fuel consumptions	Gasoline & Diesel	Historical data	24 office workers
3. Transportation stage	3.1 House components' transportation	Diesel	Historical data	Crane operation is also considered in this section
4. Erection (assembling) stage	4.1 Site workers	Gasoline & Diesel	Historical data	76 site workers
	4.2 Winter heating fossil fuel consumptions	Propane	Observation + Historical data	heaters 1 gallon/hour of propane 24 hours day in winter times
	4.3 Generators' fuel consumptions	Gasoline	Observation + Historical data	Consume 6 gallons of gasoline per day

3.4 Credibility and transformability of the research framework

This research is primarily based on actual data, and uncertainties in the observations are verified by theoretical formulae which add more credibility to the research. The research framework captures all activities in the pre-panelized process. Thus, the research framework can be applied for CO_2 assessment of pre-panelized process in general. Also, the transformability of the research method is shown through examination of the method in a case study.

Chapter 4: Research Implementation and results

4.1 General project information

Compared to conventional stick-built construction, pre-panelized construction offers the benefits of accelerated construction time, improved quality, decreased material waste, and reduced hazards and worker injuries. It also contributes to sustainability by substantially reducing the energy usage and associated greenhouse gas (GHG) emissions in the construction process (Lu, 2009). As opposed to site-built construction, in pre-panelized construction walls and floors are produced in a factory and then transported to the site for installation. This research focuses on quantifying the environmental impact of panelized construction and developing an associated carbon footprint benchmark.

As an empirical study, the research is conducted based on data collected from Landmark Building Solution (LBS). The new 80,000 ft^2 manufacturing facility of LBS is equipped with an automatic wall production line, two computer numerical control (CNC) floor tables (see Figure 6), and a designed capacity to produce wall and floor panels for 3-4 homes per 8-hour shift. Officially launched in 2012, LBS' plant now has over 160 staff, including 9 site managers, 24 office staff, 54 plant workers, and 76 site workers. Flame X[1] and All Weather Windows[2] are two main suppliers of the plant. Current LBS operations include prefabricating open wall and floor panels in the plant with sprayed insulation and installed doors and windows; transporting building components to the site; and then erecting

[1] Lumber manufacturer company in Alberta, Canada
[2] Door/Window manufacturer company in Alberta, Canada

them on site. The main focus of this research is on assessing the direct GHG emissions from LBS' operations, which are measured using a life cycle assessment (LCA) approach. Data is collected in the period of January to December, 2012 and analyzed in order to build a generic carbon footprint benchmark. During this period, LBS produced and erected 94,105.39 m^2 of single- and multi-family homes. Figure 5 shows the breakdown of LBS' monthly outputs.

Figure 4 LBS factory

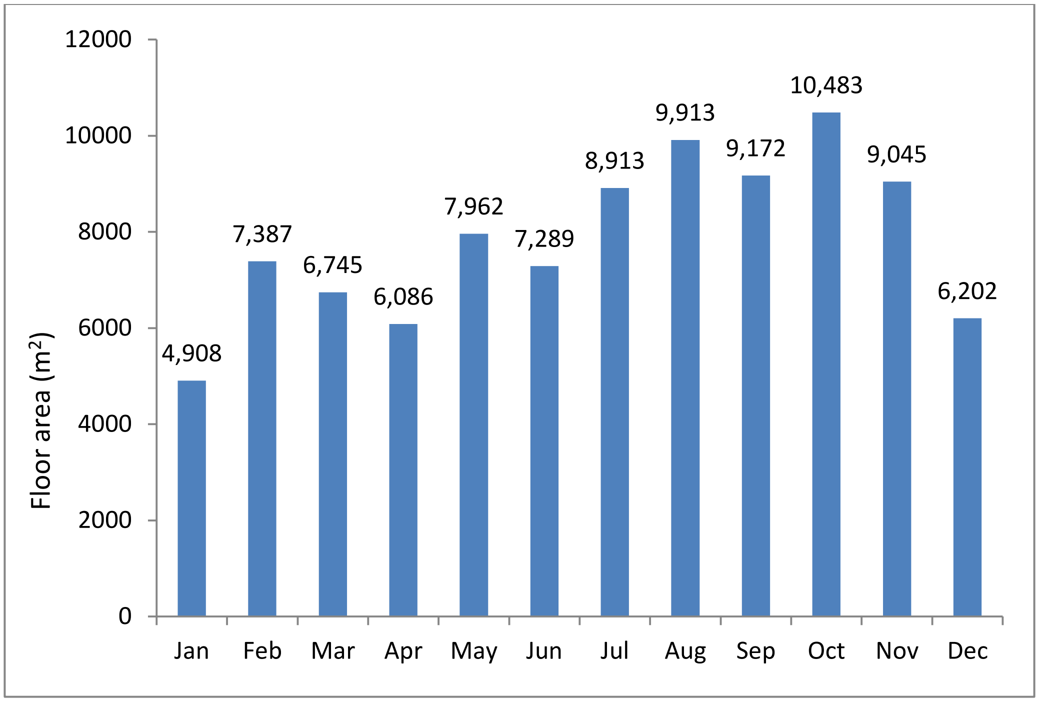

Figure 5 LBS' monthly output breakdown in 2012

4.2 LBS' details of the direct carbon footprint evaluation process

4.2.1 Lumber delivery: Delivery of lumber to LBS is carried out by rental trailers. Empty trailers begin their trip from Continental[3] (a trailer rental company in Alberta, Canada) to Flame X. Based on observations, a full trip cycle, including warming up the truck, travelling to Flame X, loading, travelling to LBS, unloading, and returning to Continental, takes 8.42 hours on average. Continental charges LBS based on operation hours. Based on actual data (the time charged by rental company) the average trip cycle is approximately 9.16 hours. Also based on observations and truck manuals for the identified truck models, truck fuel consumption is assumed to be 20 L/hr. In order to refine the results, a relative factor is defined, and average CO_2 emissions due to lumber delivery are calculated as below. Figure 6 shows variations in CO_2 emissions from delivery of

[3] Trailer rental company in Edmonton, Alberta, Canada

lumber to LBS. Average CO_2 emission levels were used for January, February, and December since there was not enough data for these months.

$$\text{Relative factor} = \frac{\text{Cycle duration based on observations}}{\text{Cycle duration based on actual data}} = \frac{8.42}{9.16} = 0.92$$

(Equation 2)

$$\begin{aligned}\text{Monthly average } CO_2 \text{ due to lumber delivery} \\ &= (\text{Relative factor}) \\ &\times (\text{Average cycle duration based on actual data}) \\ &\times (\text{Hourly fuel consumption}) \times (\text{Emission factor}) \\ &= \frac{0.92 \times 116.34 \times 20 \times 2.663}{1000} = 5.69 \text{ tons}\end{aligned}$$

(Equation 3)

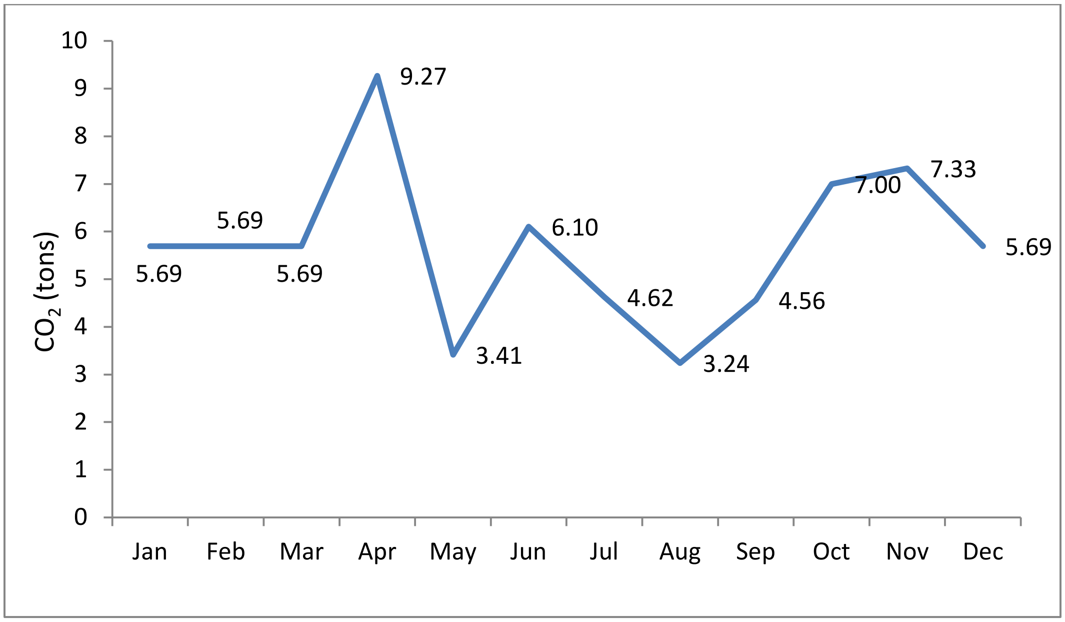

Figure 6 Lumber delivery monthly CO_2 emissions

4.2.2 Door and window delivery: All Weather Windows' trailers deliver doors and windows to LBS once per day. Based on observations and information in truck manuals for the identified truck models, average hourly fuel consumption for All Weather Windows' trucks is assumed to be 20 L/hr, and the estimated trip cycle time is 1 hour. The approximate distance between All Weather Windows and LBS is 31 km. Based on this information, the average monthly CO_2 emissions due to delivery of doors and windows is 1.11 tons. Figure 7 demonstrates monthly CO_2 emission levels for door and window delivery. Average CO_2 emissions due to door and window delivery is quantified as follows.

$$\text{Average monthly } CO_2 \text{ emissions due to door and window delivery}$$

$$= \text{Average trip cycle time (hr)} \times \text{hourly fuel consumption} \left(\frac{\text{L}}{\text{hr}}\right)$$

$$\times \text{Average number of working days}$$

$$\times \text{Diesel emission factor} \left(\frac{\text{kg}}{\text{L}}\right)$$

$$= 1 \text{ (hr)} \times 20 \left(\frac{\text{L}}{\text{hr}}\right) \times 21 \text{(day)} \times 2.663 \left(\frac{\text{kg}}{\text{L}}\right) = 1.11 \text{ tons}$$

(Equation 4)

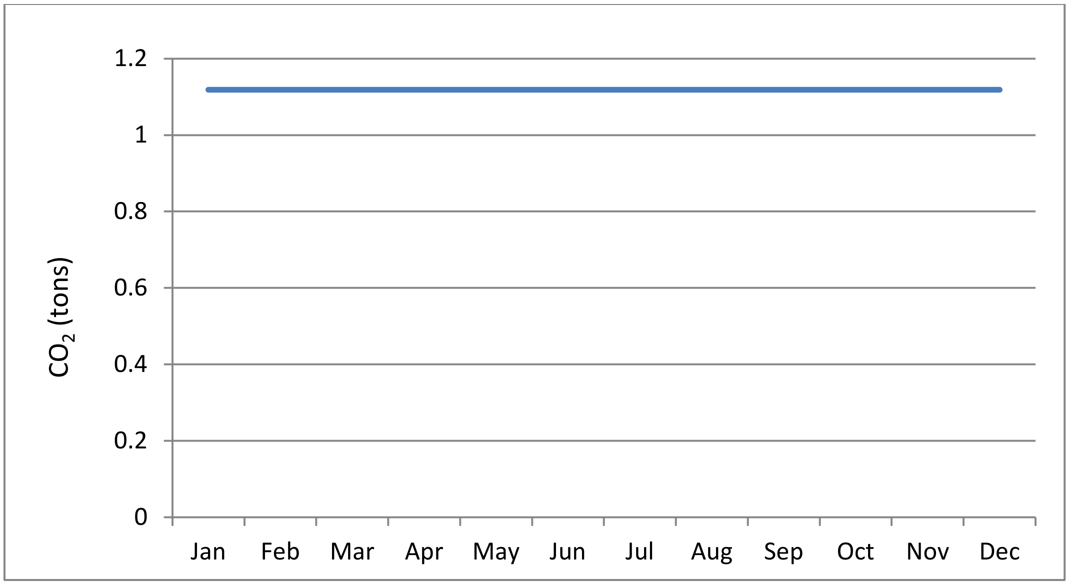

Figure 7 Door and window delivery CO_2 emissions

4.2.3 Delivery truck fuel consumption verification: Based on the manuals of vehicles in the fleet as well as on the formula proposed by Robert (2006), truck fuel consumption is verified as follows.

$$\text{Hourly fuel consumption}\left(\frac{\text{Gal}}{\text{hr}}\right) = 0.04 \times 350\ \text{hp} \times \text{Operation Factor}\ (\text{O}_\text{f})$$

(Equation 5)

where:

$$0.04 \times 350 \times 0.5 = 7\ \text{Gal/hr} = 26.49\ \text{L/hr}$$

The operation factor in this formula represents road conditions such as slopes. Using 0.5 for this factor takes the worst condition into account. Based on vehicle manuals the average horsepower (hp) of trucks in the fleet is assumed to be 350 hp. Also, according to observations, trucks are idling an average of 25% of the time for such reasons as warming up and unloading. Based on the observed road conditions for the delivery route, it is evident that the operation factor should be considered to be less than 0.5. Thus, 20 L/hr is assumed to be close to the average fuel consumption.

4.2.4 Utilities (electricity and natural gas): The LBS facility, plant machinery, and associated offices use electricity and natural gas. Based on the monthly utility bills of LBS, electricity consumption is measured in kilowatt hours, and natural gas (for heating the LBS facility) is measured in gigajoules (GJ). Figure 8 and Figure 9 show monthly CO_2 emissions due to electricity consumption and natural gas consumption, respectively. The diagram shows almost constant levels for electricity consumption (49.12 tons to 56.98 tons), whereas natural gas consumption fluctuates seasonally and, as Figure 9 shows, is substantially higher during winter. Average CO_2 emissions due to electricity consumption and natural gas consumption are calculated as below.

$$\text{Electricity average monthly } CO_2 \text{ emission}$$
$$= \text{Average monthly electricity consumption (Kwh)}$$
$$\times \text{ Electricity emission factor } \left(\frac{\text{kg}}{\text{Kwh}}\right) = 62604.55 \times 0.83$$
$$= 51.96 \text{ tons}$$

(Equation 6)

Natural gas average monthly CO_2 emission

$$= \text{Average monthly natural gas consumption(GJ)}$$

$$\times \text{Volume coefficient}\left(\frac{m^3}{GJ}\right) \times \text{Natural gas emission factor}\left(\frac{kg}{m^3}\right)$$

$$= 500.66\ (GJ) \times 26.137\left(\frac{m^3}{GJ}\right) \times 1.918\left(\frac{kg}{m^3}\right) = 25.09\ \text{tons}$$

(Equation 7)

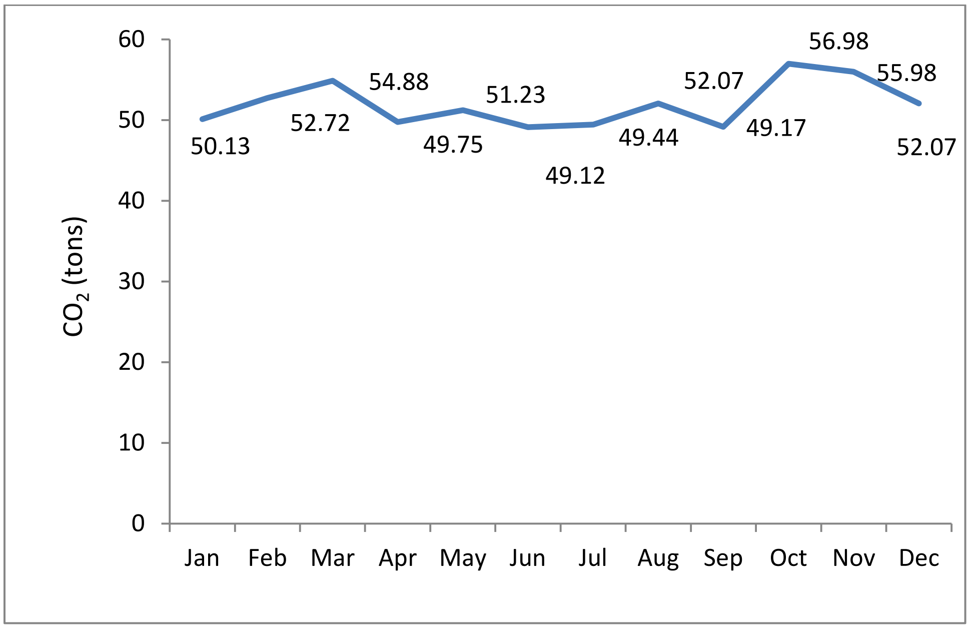

Figure 8 Monthly CO_2 emissions due to electricity usage

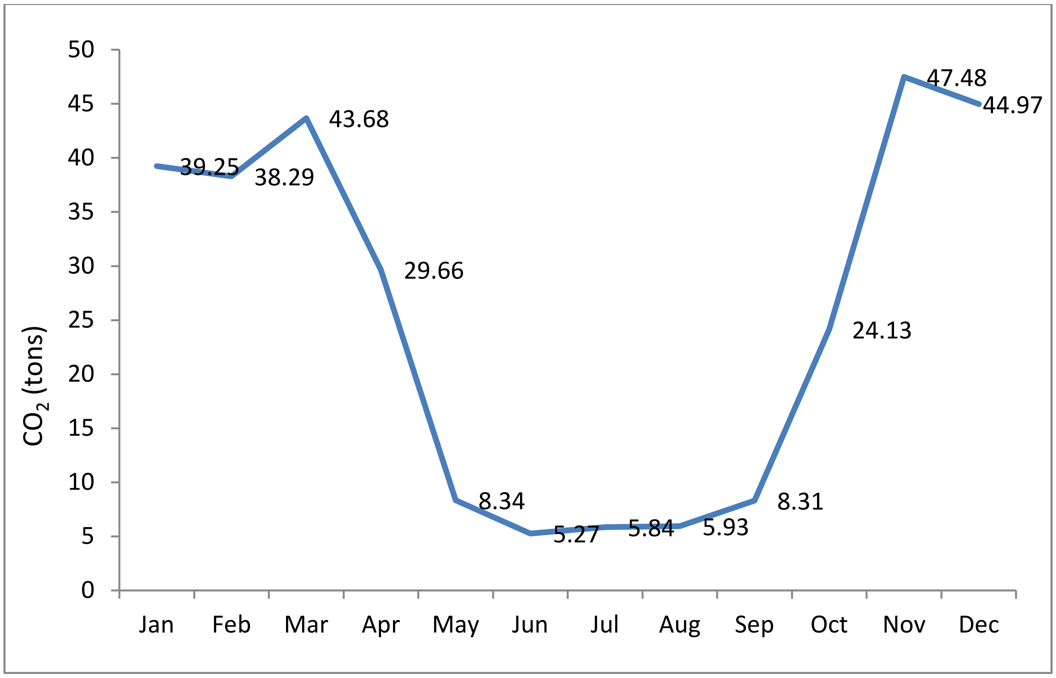

Figure 9 CO_2 emissions due to natural gas usage

4.2.5 Propane consumption in the plant: In LBS' facility, propane is used to operate the forklifts. The monthly CO_2 emissions diagram for propane consumption in the plant (Figure 10), with the exception of the month of November, shows only small variations. The average monthly CO_2 emissions for propane usage is calculated to be 2.82 tons based on monthly totals from January to December, with the outlier month of November omitted from the calculation (Propane consumption in November was significantly higher than in other months because plant propane purchase bills were mixed with site propane bills). Average CO_2 emissions due to propane consumption in the plant are quantified as follows.

Propane average monthly CO2 emissions

$$= \text{Average monthly propane consumption (L)}$$

$$\times \text{Propane emission factor} \left(\frac{\text{kg}}{\text{L}}\right) = 2110.36\ (\text{L}) \times 1.51 \left(\frac{\text{kg}}{\text{L}}\right)$$

$$= 2.52\ \text{tons}$$

(Equation 8)

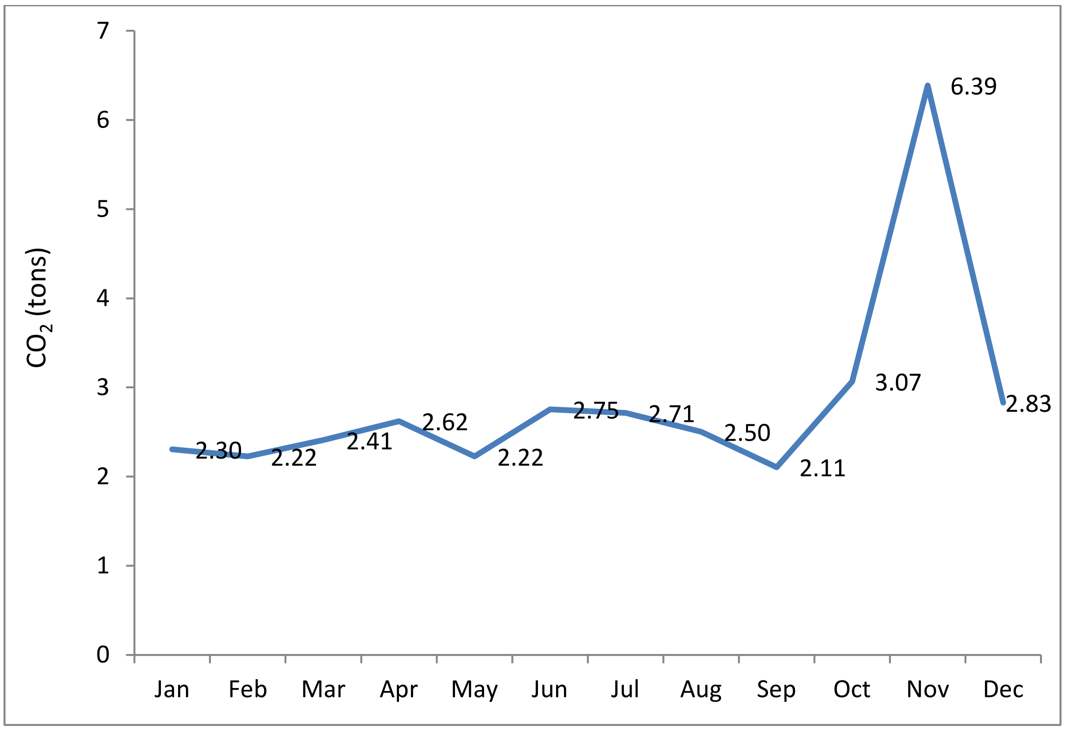

Figure 10 Monthly CO_2 emissions due to propane usage

4.2.6 Employee transportation: Employee transportation includes plant employee transportation, office employee transportation, field employee transportation, and site manager transportation. The results from calculating CO_2 emissions of employees show that transportation of 54 LBS plant workers, 24 office staff, 76 field workers, and 9 site managers have associated average emissions of 8.91, 1.46, 8.97, and 0.03 tons of CO_2 per month, respectively.

Compared to other employees, the 9 site managers have a smaller share in CO_2 emissions which is 0.03 tons per month. Figure 11, Figure 12, Figure 13, and Figure 14 demonstrate monthly CO_2 emissions due to travel of plant workers, office workers, site workers, and site managers, respectively. Since employees' transportation patterns are constant throughout the year, CO_2 emission levels due to employee transportation are also constant. Average CO_2 emissions due to employee transportation are quantified as follows.

$$
\begin{aligned}
&\text{Employee transportation average monthly } \mathrm{CO_2} \text{ emissions} \\
&\qquad = \text{Total number of employees} \\
&\qquad \times \text{Average number of working days per month} \\
&\qquad \times \text{Average daily travel distance (km)} \\
&\qquad \times \text{Average vehicle fuel consumption } \left(\frac{\mathrm{L}}{100\ \mathrm{km}}\right) \\
&\qquad \times \text{Gasoline emission factor}
\end{aligned}
$$

(Equation 9)

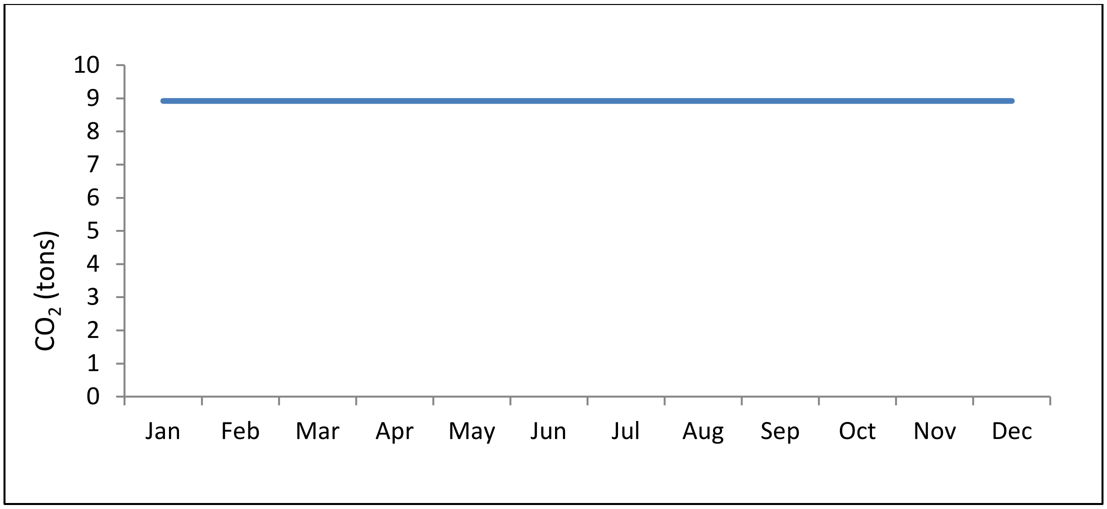

Figure 11 Monthly CO_2 emissions due to travel of plant workers

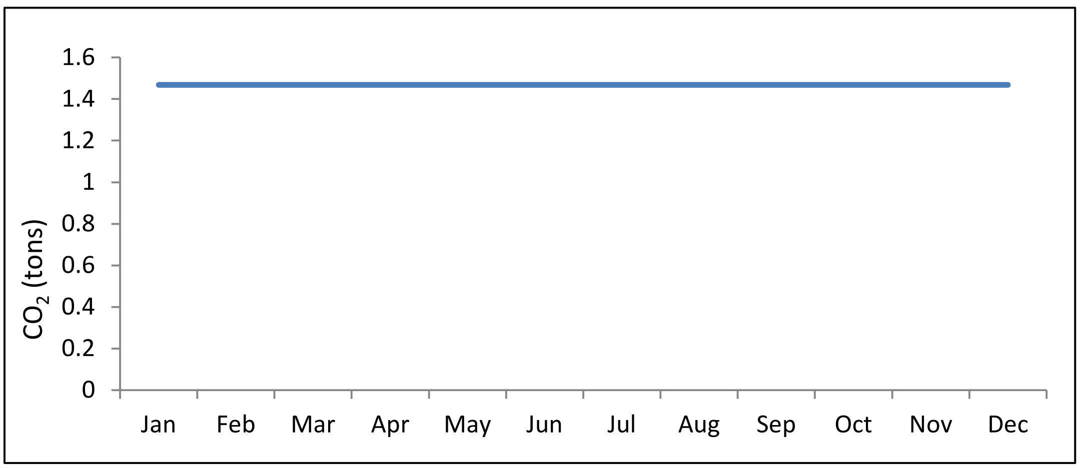

Figure 12 Monthly CO_2 emissions due to travel of office workers

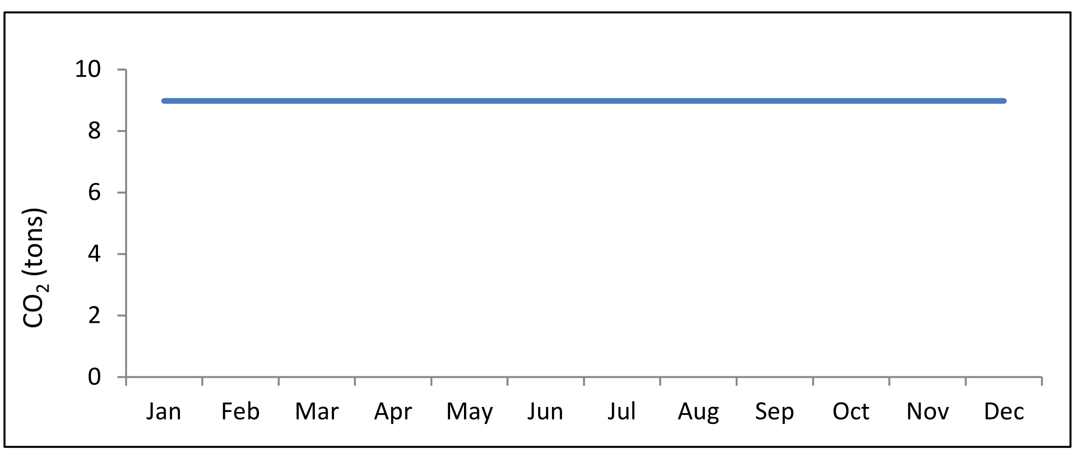

Figure 13 Monthly CO_2 emissions due to travel of site workers

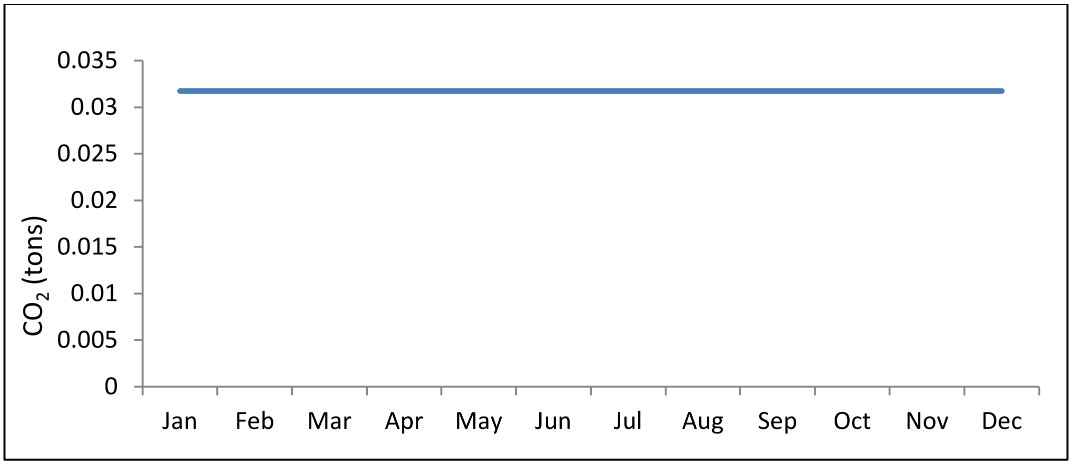

Figure 14 Monthly CO_2 emissions due to travel of site managers

4.2.7 Panel transportation and crane operation: The LBS fleet delivers the pre-panelized wall and floor panels to job sites. All diesel fuel bills in the accounting records primarily represent LBS delivery trucks' fuel consumptions, this data also accounts for diesel consumption from crane operations. Due to difficulties in separating these two categories of consumption, the monthly CO_2 emissions diagram of diesel consumption (Figure 15) includes both crane and truck operation. The average monthly CO_2 emissions associated with panel transportation and crane operation are 29.08 tons, and are calculated based on monthly totals from June to December only (due to reorganization of the fleet). Average CO_2 emissions due to panel transportation and crane operation are quantified as below.

$$\text{Average monthly } \mathrm{CO_2} \text{ emissions due to panel transportation and crane operation}$$
$$= \text{Average monthly diesel consumption (L)} \times \text{ Diesel emission factor } \left(\frac{\mathrm{kg}}{\mathrm{L}}\right)$$
$$= 10919.07\ (\mathrm{L}) \times 2.663 \left(\frac{\mathrm{kg}}{\mathrm{L}}\right) = 29.08 \text{ tons}$$

(Equation 10)

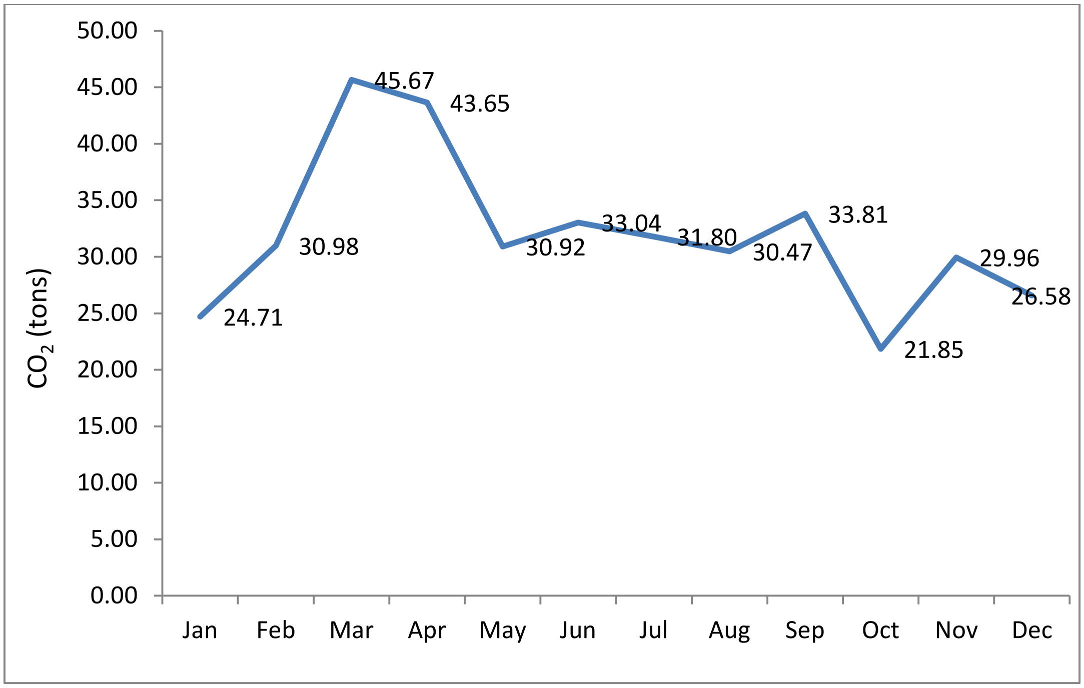

Figure 15 Monthly CO_2 emissions due to diesel consumption

4.2.8 Field winter heating: In the field, propane is used for space heating of basements. Winter heating begins in October and continues until the middle of March. 100,000-Btu propane heaters are used to heat basements for 24 hours a day for almost 6 months of the year. Although winter heating proceeds after the framing stage, the duration is limited to the wood framing stage. Historical data from LBS for 2012 shows the average cycle time of wood framing, from the beginning of the on-site erection to completion of the roof erection, to be 14.08 days. Given that the heaters burn 1 gallon (3.785 Litres) of propane per hour, the associated CO_2 emissions for heating a 1,600 ft^2 (148.64 m^2) house are calculated as follows; (also, Figure 16 shows monthly CO_2 emission levels for winter heating).

Winter heating CO_2 emissions per house

$$= \text{Propane consumption (L/hr)} \times \text{Operation duration (hr)}$$

$$\times \text{Cycle time(day)} \times \text{Propane Emission Factor}$$

$$= 1\,\frac{\text{gal}}{\text{hr}} \times 3.785\,\frac{\text{L}}{\text{gal}} \times 24\,\frac{\text{hr}}{\text{day}} \times 14.08\,\frac{\text{days}}{\text{house}} \times 1.51\,\frac{\text{kg}}{\text{L}}$$

$$= 1.93\,\frac{\text{tons}}{\text{house}}$$

(Equation 11)

Where;

$$\text{Winter heating } CO_2 \text{ emissions per sq ft} = \frac{1.93}{1{,}600} = 0.0012\,\frac{\text{tons}}{\text{sq ft}}$$

Annual floor area production based on actual data = 1,012,942 sq ft

$$\text{Winter heating average monthly } CO_2 \text{ emission} = \left(\frac{1{,}012{,}942 \times 0.0012}{2}\right) \div 12$$

$$= 50.95\,\frac{\text{tons}}{\text{month}}$$

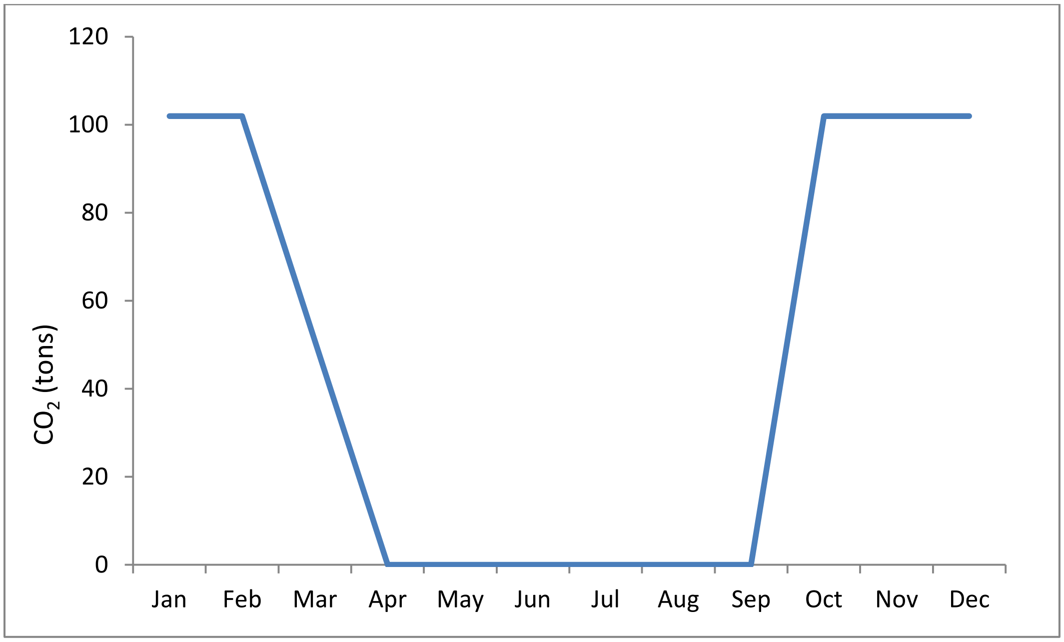

Figure 16 Monthly CO_2 emissions due to winter heating

4.2.9 Generator operation: Generators and compressors are used in the field for various purposes such as nailing. Based on observations and review of user manuals, generators use 6 gallons (22.7125 Litres) of gasoline per day. Historical data from LBS for 2012 shows that the average cycle time for framing is 3.6 days. As such, the associated CO_2 emissions from generator operations are calculated as follows; (Figure 17 shows monthly CO_2 emission levels for site generators).

$$\text{Generator operation } CO_2 \text{ emissions per house} = \text{Gasoline consumption}\left(\frac{\text{L}}{\text{day}}\right) \times \text{Cycle time(day)} \times \text{Gasoline Emission Factor} = 6 \times 3.785 \times 3.6 \times 2.289 = 0.187\,\frac{\text{tons}}{\text{house}}$$

(Equation 12)

$$\text{Generator operation } CO_2 \text{ emissions per square feet} = \frac{0.187}{1{,}600} = 0.000117\,\frac{\text{tons}}{\text{sq ft}}$$

$$\text{Generator operation average monthly } CO_2 \text{ emission} = \frac{0.000117 \times 1{,}012{,}942}{12} = 9.87\,\frac{\text{tons}}{\text{month}}$$

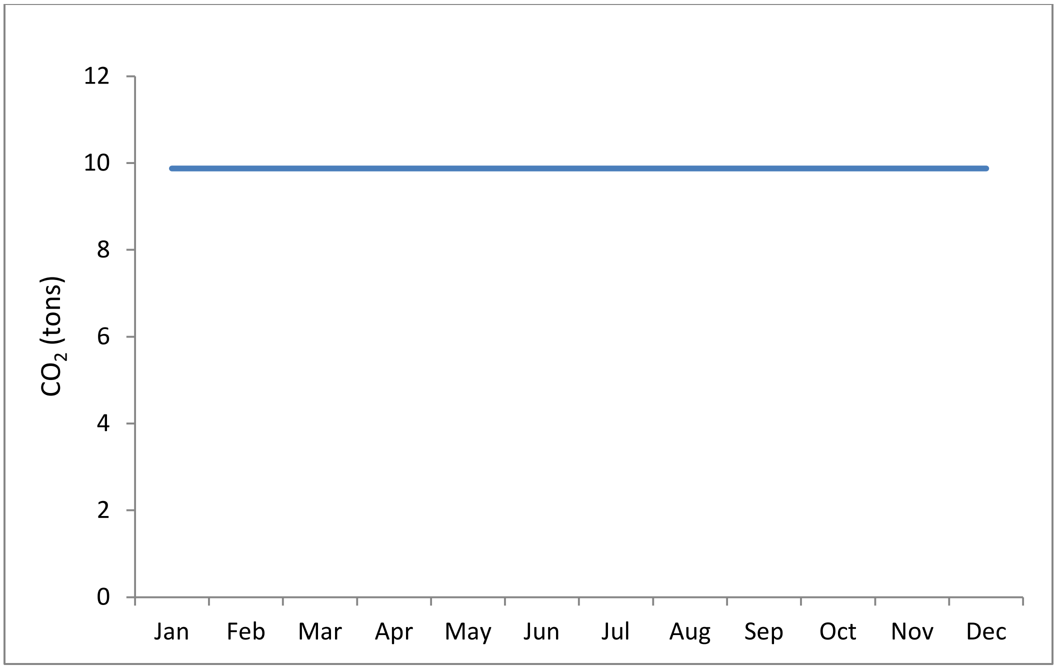

Figure 17 Monthly CO_2 emissions due to site generators

4.3 LBS' monthly average direct CO_2 emissions results

Final results reveal that utilities (electricity and natural gas), winter heating, and panel transportation, with 39%, 26%, and 15% of associated CO_2 emissions for the framing process, respectively, contribute to a greater extent to total monthly direct CO_2 emissions. The CO_2 emissions associated with the natural gas and electricity used in LBS are nearly constant, and these nearly constant emissions depend on outside temperature rather than on plant production. CO_2 emissions due to such emission elements as deliveries, field winter heating, and transportation, on the other hand, vary based on production level. Table 3 and Figure 18 shows each stage's contribution to total direct CO_2 emissions. To quantify the CO_2 emissions of the pre-panelized process, it should be noted, a metric is required. In this study CO_2 emissions are quantified based on CO_2 emissions per house and CO_2 emissions/m^2 of floor area. Based on actual LBS production output, it is assumed that LBS has an average monthly output of 60 homes per month, with an average floor area of 1,600 ft^2 (148.64 m^2) per house. Dividing the total annual CO_2 emissions by the total number of produced units in 2012 shows that the construction of a 148.64 m^2 house produces 3.68 tons of CO_2. Since conducting an activity is not totally dependent on the floor area, results are more sensitive to the number of produced houses. As such, the average floor area of 1,600 ft^2 (148.64 m^2) could be considered as a good assumption in calculating the number of houses produced in a year. The following conclusions can be made based on the final results and observations:

- Utilities, winter heating, and panel transportation, with 39%, 26%, and 15% of associated CO_2 emissions for the framing process, respectively, contribute to a greater extent to total monthly direct CO_2 emissions. Thus, these activities could be considered as the best targets for CO_2 emission reduction of the pre-panelized process.
- Propane usage in the plant is almost consistent, and correlates with peak output based on observation. The actual collected data from the plant substantiates this pattern with the exception of November. CO_2 emissions from plant propane usage are calculated based on an 11-month average of Jan – Dec, except November.
- The LBS fleet includes site material delivery and return trucks, semi-trailers for panel transportation, cranes, and field spray foam trucks. The diesel consumption was almost consistent from May to September and then reduced in October when the field spray was delegated to

subcontractors. As field spray is still a part of LBS' operations even though it is no longer reflected in the fuel consumption records, the average diesel consumption in May to September is used as a reasonable rate for the assessment.

- Material delivery needs to be matched to the plant outputs. The turnover of the material in the LBS yard is generally less than one month. In 2012, the output of the plant peaked in August to November.
- The gas consumption of generators and compressors on site is a function of production output. Based on actual data, the average of 3.6 days is considered as the per unit duration for running this equipment in the field.

Table 3: LBS' average monthly CO_2 emissions

Emission Element	**CO_2 footprint per month**
Electricity usage	51.96
Natural gas usage	25.09
Plant equipment propane consumption	2.82
Transportation + crane diesel consumption	29.08
Lumber delivery fuel consumption	5.69
D/W delivery fuel consumption	1.11
LBS workers fuel consumption	8.91
Site workers fuel consumption	8.97
LBS office fuel consumption	1.46
Site managers fuel consumption	0.03
Field winter heating propane consumption	50.95
Site generators fuel consumption	9.87
Total (tons) per month	195.99
Total floor area production for 12 months (m^2)	94,105.39
CO_2 emissions/m^2 of output (kg/m^2)	24.75
Total CO_2 emissions per house (tons)	3.68

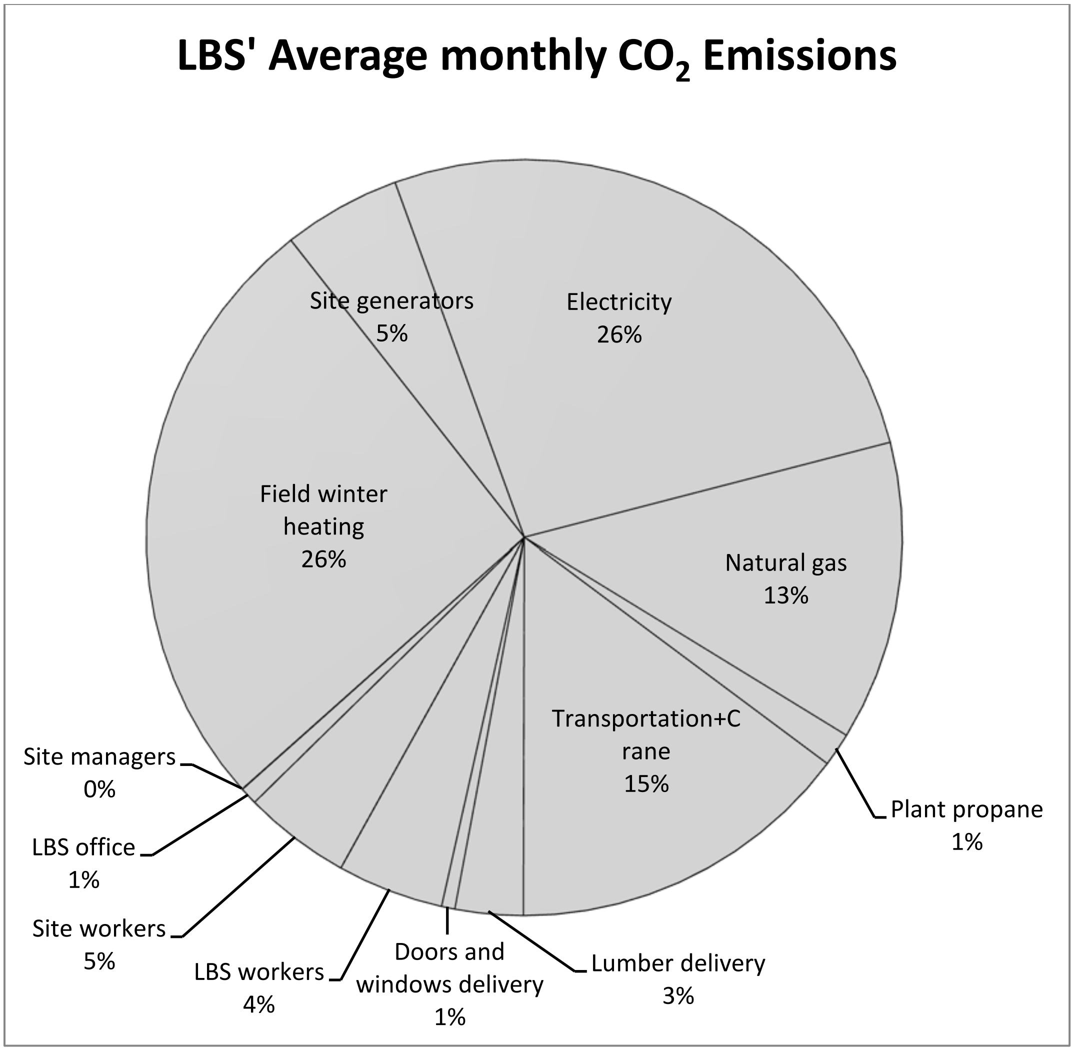

Figure 18 LBS' average monthly CO_2 emissions

4.4 Monthly analysis of direct GHG emissions

By studying the monthly GHG emissions of LBS' operations, the following conclusions are drawn:

- Some operations' emissions are consistent from month to month, such as employee transportation. As long as the number of office staff, site managers, plant workers, and site crew members remains constant, the associated fuel consumption remains the same. Fuel consumption for window/door delivery is also a consistent value, as there is one delivery from the supplier every workday.

- Seasonal emissions such as those from the burning of natural gas, which is mainly used for space heating, are dependent on outside temperature. Electricity usage also has a slight correlation with the outside temperature, with almost 10% variation between summer and winter. However, since most of the electricity consumption is associated with lighting and running of machinery, the associated emissions of this usage are considered to be consistent. The emissions associated with the portion of electricity usage for space heating and ventilation are considered to be seasonal.
- Theoretically, the fuel consumptions of lumber transportation, crane operation, and panel shipping should be functions of production output. However, materials are usually purchased in large volumes at lower prices and stored in the yard for weeks. As such, diesel consumption is more dependent on the structure of fleet usage than on the number of houses erected.
- Compared to monthly average CO_2 level monthly average CO_2 emission levels show almost 32% overestimating in summer and almost 30% underestimating in winter.

Table 4 represents the evaluative elements and associated CO_2 emissions. As the total results show, seasonal emissions have a higher impact on total monthly CO_2 emissions than do consistent emissions. As Figure 19 and Figure 20 show, the total monthly CO_2 emission pattern roughly corresponds to natural gas and winter heating patterns. Thus, outside temperature has a greater impact on LBS' direct CO_2 emissions than do other factors. In this regard, monthly average CO_2 emission level could be considered as a benchmark for CO_2 emission reduction of the pre-panelized process, with the aim of reducing the monthly average CO_2 emission level.

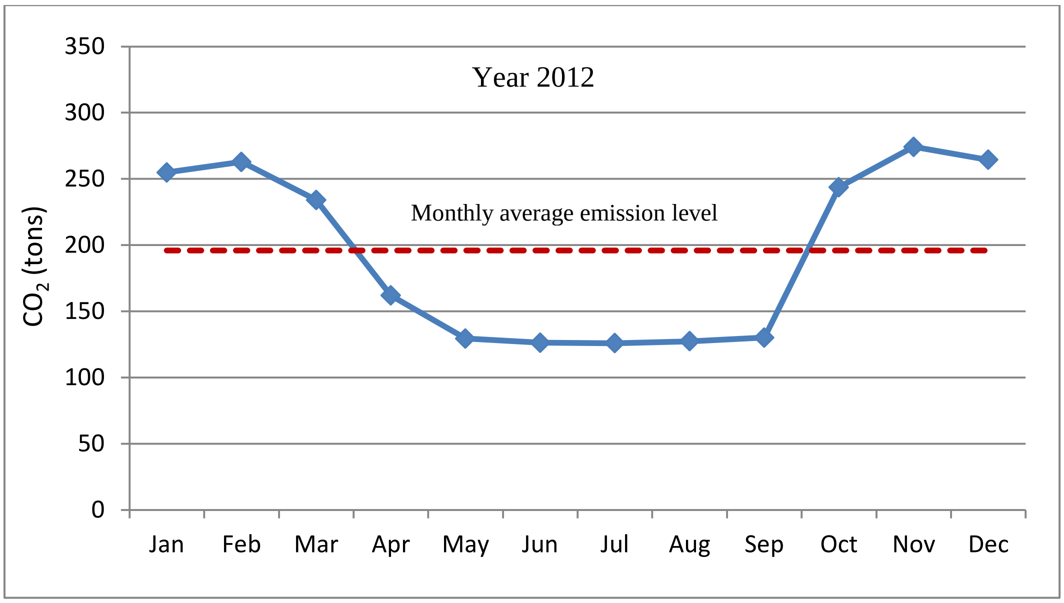

Figure 19 LBS' monthly CO_2 emissions

Table 4: Monthly CO_2 emissions due to emission elements (in tons)

	Electricity	Natural gas	Propane	Transportation + Crane	Lumber delivery	Door and window delivery	LBS workers	Site workers	LBS office	Site generators	Winter heating	Site managers	Total
Jan.	50.13	39.25	2.82	24.71	5.69	1.12	8.92	8.98	1.47	9.87	101.90	0.03	254.90
Feb.	52.72	38.29	2.82	30.98	5.69	1.12	8.92	8.98	1.47	9.87	101.90	0.03	262.80
Mar.	54.88	43.68	2.82	45.67	5.69	1.12	8.92	8.98	1.47	9.87	50.95	0.03	234.09
Apr.	49.75	29.66	2.82	43.65	5.69	1.12	8.92	8.98	1.47	9.87	0.00	0.03	161.96
May	51.23	8.34	2.82	30.92	5.69	1.12	8.92	8.98	1.47	9.87	0.00	0.03	129.39
Jun.	49.12	5.27	2.82	33.04	5.69	1.12	8.92	8.98	1.47	9.87	0.00	0.03	126.34
Jul.	49.44	5.84	2.82	31.80	5.69	1.12	8.92	8.98	1.47	9.87	0.00	0.03	125.98
Aug.	52.07	5.93	2.82	30.47	5.69	1.12	8.92	8.98	1.47	9.87	0.00	0.03	127.37
Sep.	49.17	8.31	2.82	33.81	5.69	1.12	8.92	8.98	1.47	9.87	0.00	0.03	130.19
Oct.	56.98	24.13	2.82	21.85	5.69	1.12	8.92	8.98	1.47	9.87	101.90	0.03	243.77
Nov.	55.98	47.48	2.82	29.96	5.69	1.12	8.92	8.98	1.47	9.87	101.90	0.03	274.23
Dec.	52.07	44.97	2.82	26.58	5.69	1.12	8.92	8.98	1.47	9.87	101.90	0.03	264.43
Total	623.54	301.18	33.91	383.43	68.30	13.42	106.99	107.74	17.61	118.48	560.49	0.38	2,335.49

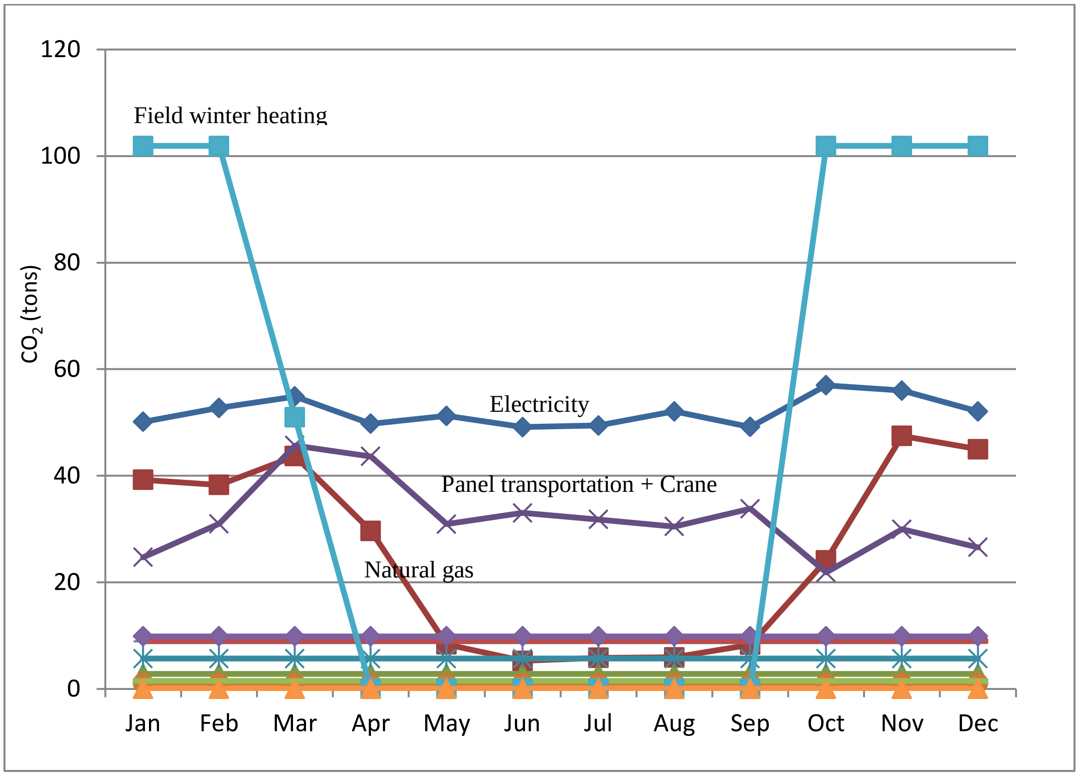

Figure 20 Monthly CO_2 emissions due to emission elements

4.5 Pre-panelized sustainability improvement (CO_2 emission reduction)

By examining the breakdown of GHG emissions from each element of LBS' process, the utilities usage of the prefabrication facility is found to account for 39% of total GHG emissions. Replacing or supplementing electricity and natural gas sources with a renewable source such as solar energy is thus expected to reduce the carbon footprint of LBS' operations significantly. Also, it is expected that reducing the factory temperature after working hours and using more insulation in the factory walls will lead to reduced utility consumption and, consequently, reduced CO_2 emissions.

Field winter heating, another major contributor, accounts for 26% of total CO_2 emissions. Reducing the wood framing duration by adding extra workers or extra shifts per day could reduce the demand for winter heating and thus reduce the level of CO_2 emission.

The fuel consumption associated with transportation of building components and with crane operation is the third largest source of GHG emissions in LBS' operations, contributing to over 15% of the total carbon footprint. From the perspective of improving sustainability, it is worth investigating the feasibility of considering a logistic planning and tracking system to optimize and control the transportation process. A fleet management system would also benefit LBS' operations by improving the efficiency of the logistic system and thus reducing fuel and labour costs. In other words a fleet management system could help in optimizing utilization of trailers with respect to their capacity and the associated loads.

4.6 Simulate and model the CO_2 emissions of the pre-panelized process

In order to model the CO_2 emissions of the pre-panelized process in the long term, historical data is required to generate appropriate distributions as the inputs to the model. For example, to model CO_2 emissions due to electricity consumption, electricity consumption records of the process for several years are required to generate a distribution for each month as an input to the model. In other words, the inputs of the model are the energy components of the fossil fuel records in the long term. Compared to a designed MS Excel spreadsheet which can calculate the CO_2 emissions of the pre-panelized process for only one year, the developed model is capable of receiving distributions as inputs and running for the desired number of iterations. Thus, the model can also generate cumulative density function (CDF) charts, histograms, and monthly CO_2 emission charts for the desired outputs. Figure 21 shows the framework for modelling the benchmark of the pre-panelized process.

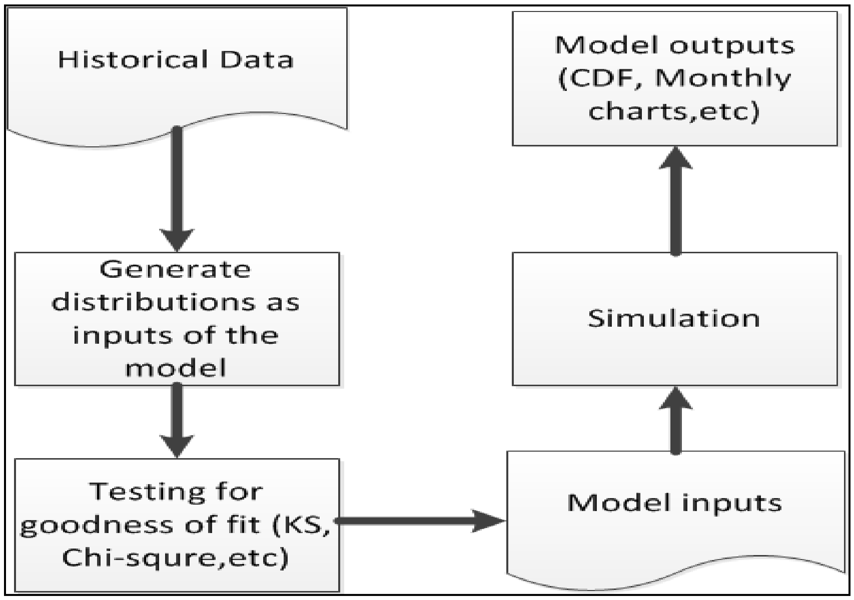

Figure 21 Pre-panelized process benchmark modelling framework

A simulation model using the general-purpose template in Simphony is developed to quantify the CO_2 emissions for each activity and the average CO_2 emissions of the whole process. In the developed model, CO_2 emissions of the process are calculated based on average CO_2 emissions per month and CO_2 emissions per house, which are considered as the outputs of the model. Figure 22 demonstrates the developed model for quantifying the CO_2 emission benchmark of the pre-panelized process in Simphony. Each composite element in the presented model contains a model which is part of the overall simulation for quantifying the average CO_2 emissions of the associated activity. The models developed for each activity are demonstrated in the Appendix.

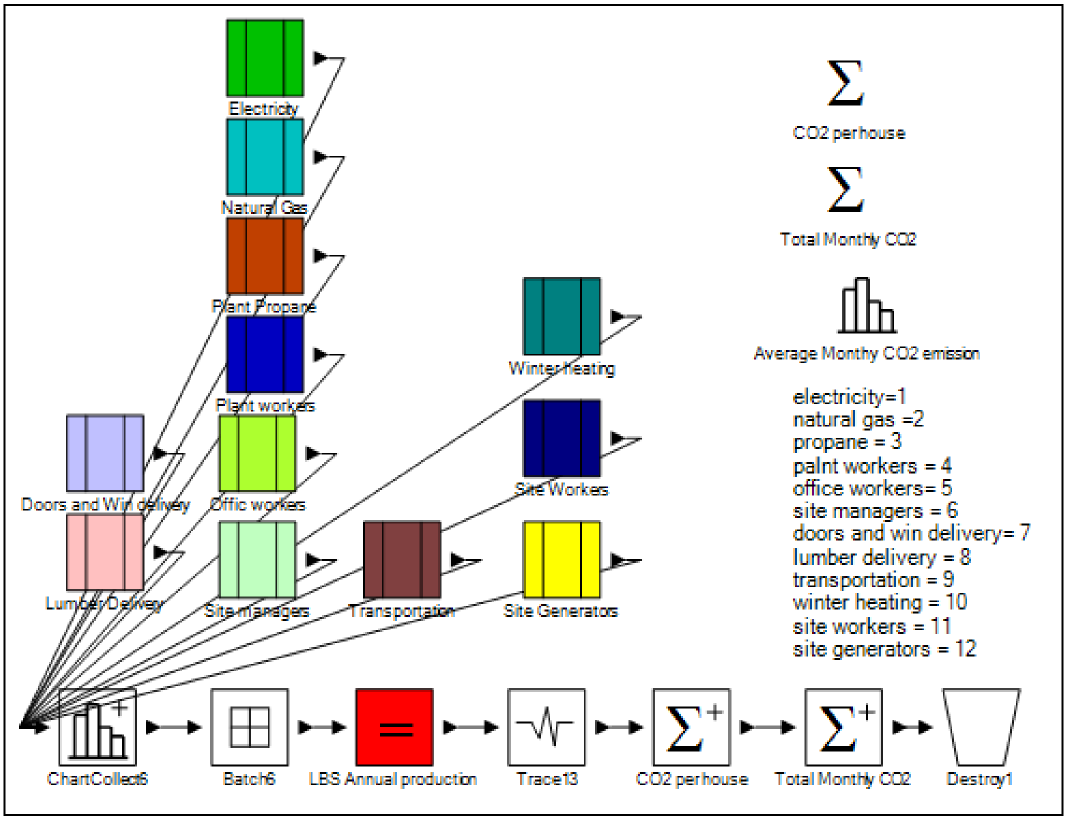

Figure 22 Pre-panelized benchmark Simphony model

Since pre-panelized construction is a relatively new method, to date there is not enough historical data to produce the distributions for the model inputs. In order to evaluate the function of the model and the model outputs, triangular distributions are assumed as the inputs of the model. The parameters of the triangular distributions (min, mean, max) are chosen to be relatively close to the average fossil fuel records in 2012 with ±10% variation. The model is run 1000 times and the average monthly CO_2 emissions of the pre-panelized process and the average CO_2 emissions/m^2 of floor area are calculated based on assumptions. Figure 23 and Figure 24 demonstrate the cumulative distribution function (CDF) and histogram for CO_2 emissions per house. Figure 25 and Figure 26 show the CDF and histogram for average CO_2 emissions of the pre-panelized process.

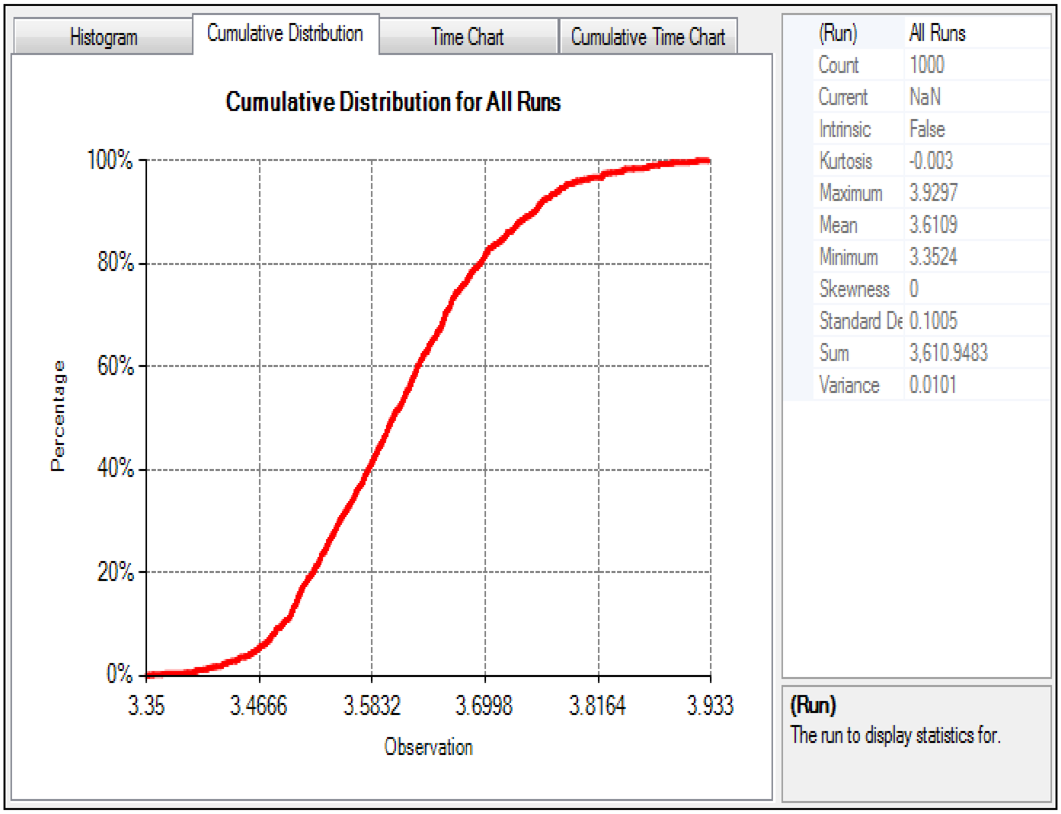

Figure 23 CDF chart for CO_2 emissions per house

The CDF chart for the CO_2 emissions per house corresponds to the likelihood of CO_2 emission levels for the associated inputs. The histogram represents the distribution of samples in the model.

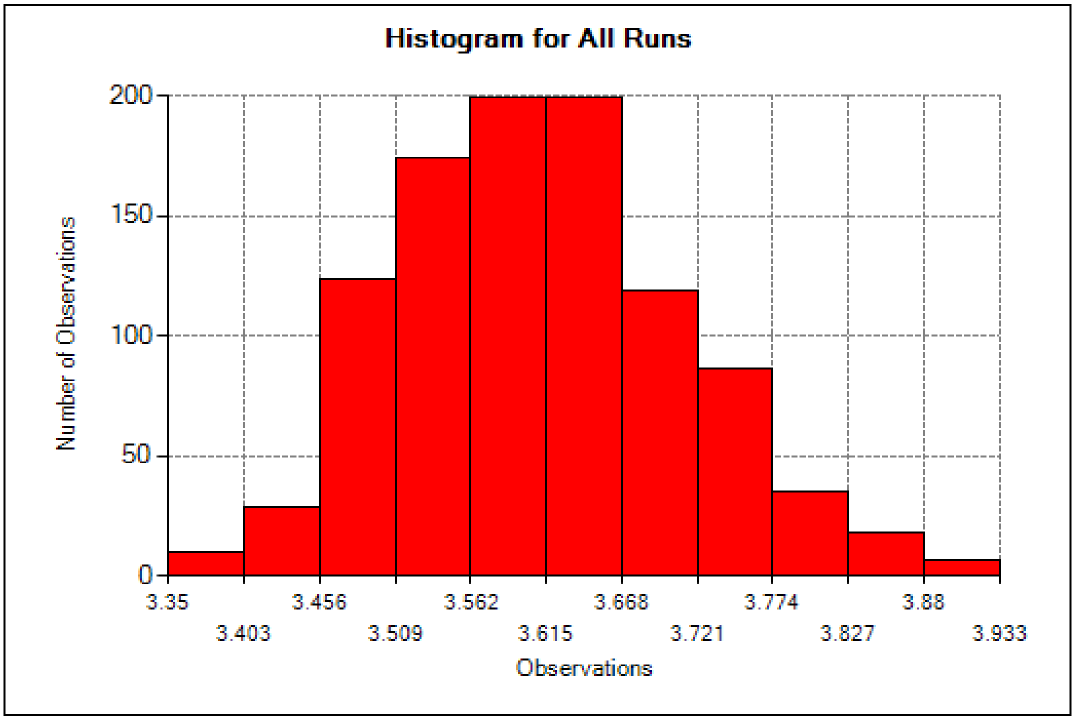

Figure 24 Histogram for CO_2 emissions per house

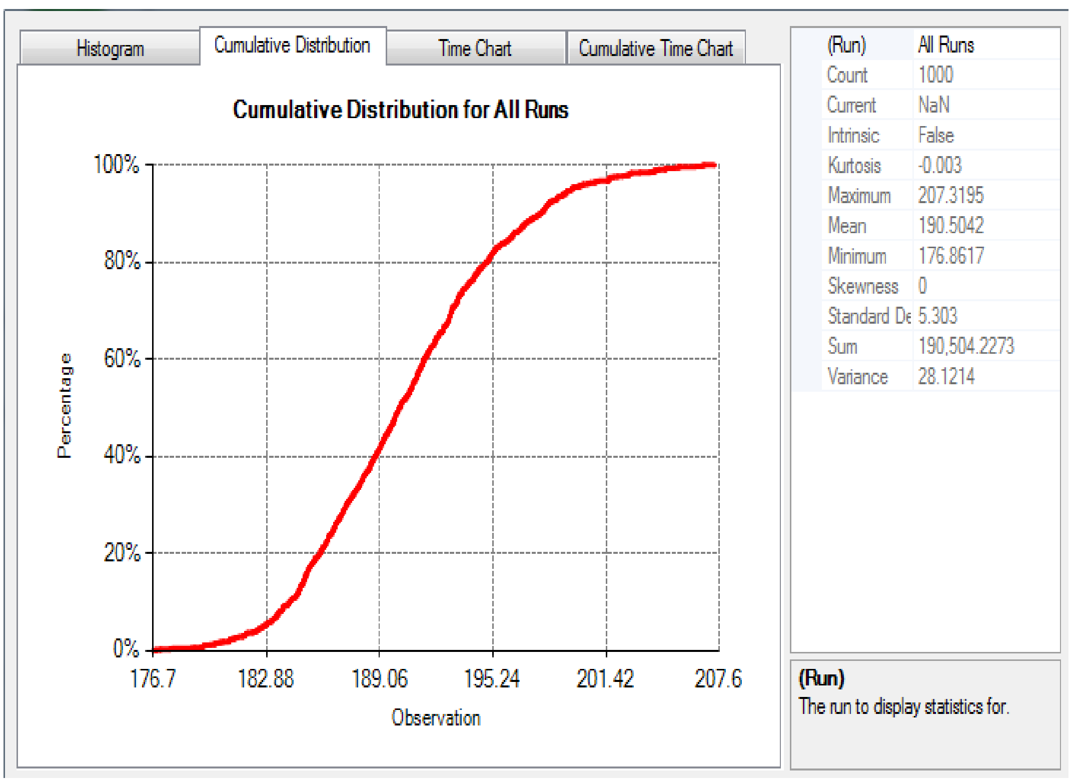

Figure 25 CDF chart for monthly average CO_2 emissions of the pre-panelized process

The CDF chart for the average monthly CO_2 emissions of the pre-panelized process corresponds to the likelihood of CO_2 emission levels for the associated inputs. For example, the likelihood of the value, 195.24 tons per month, as the average CO_2 emissions of the pre-panelized process based on is approximately 81%, as seen in Figure 25. The average CO_2 emission level of the pre-panelized process represents the baseline of the process in the long term.

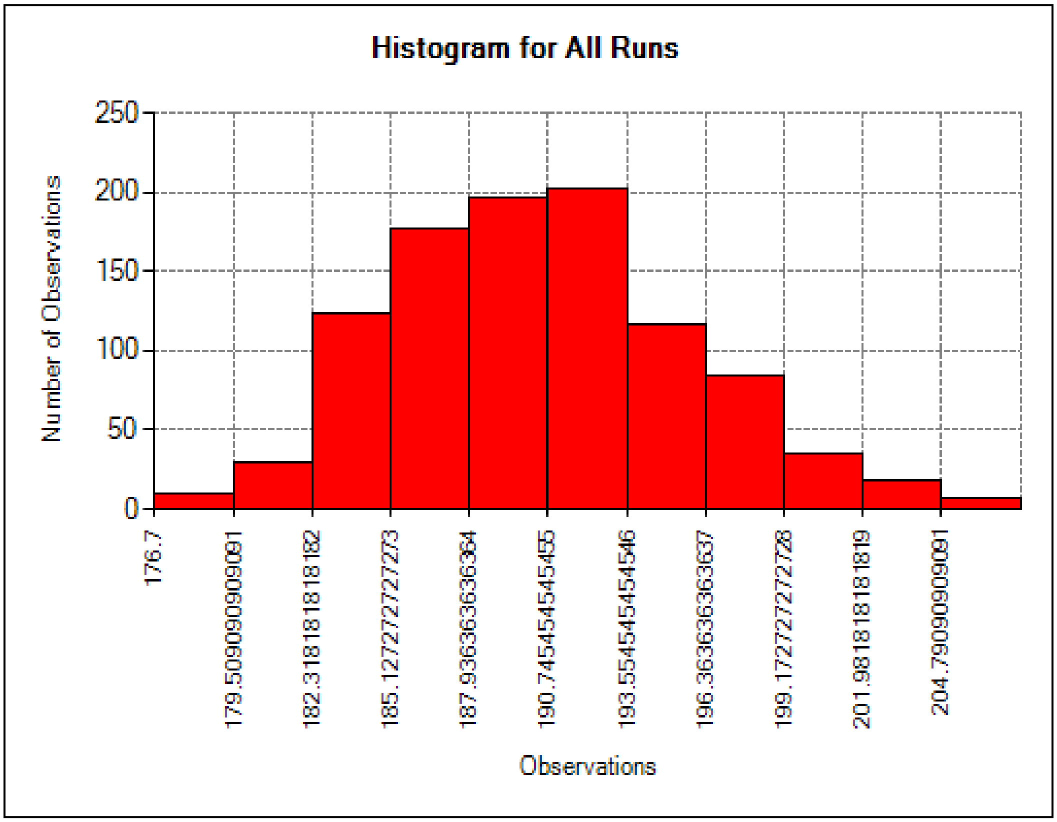

Figure 26 Histogram for average CO_2 emissions of the pre-panelized process

The other output of the developed model is an average monthly CO_2 emission diagram for contributors to the total CO_2 emissions of the pre-panelized process (benchmark). Figure 27 shows the benchmark of the pre-panelized process in the long term based on the assumed inputs.

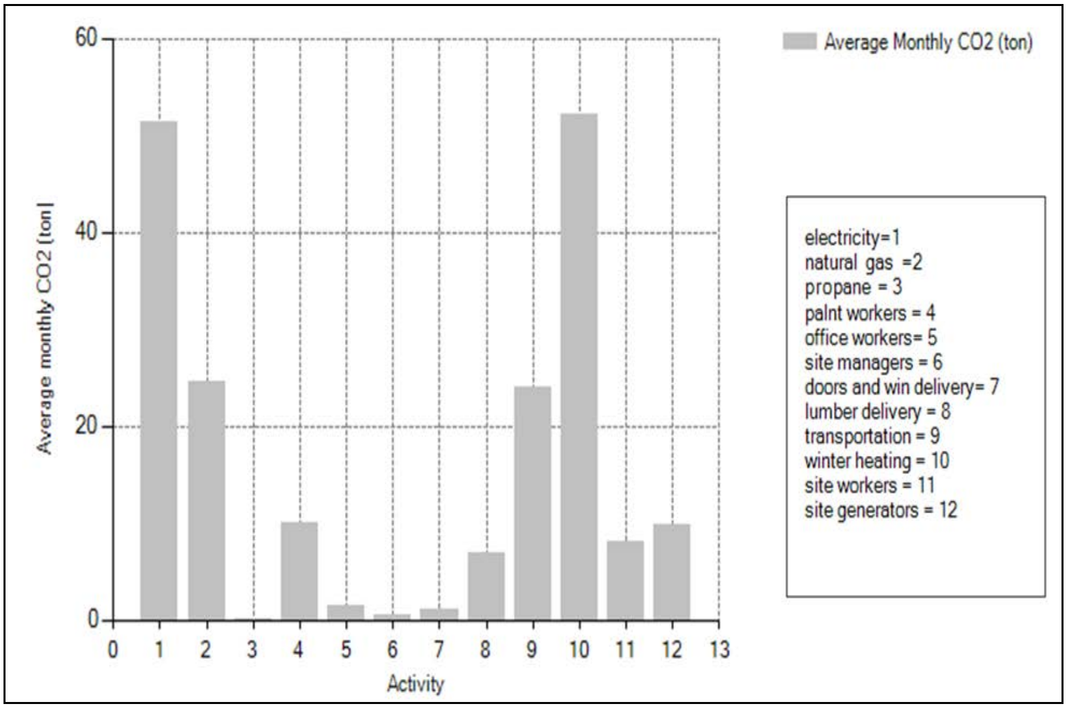

Figure 27 Pre-panelized process benchmark

4.7 Stick-built direct GHG emission evaluation process

A study conducted by Mah (2011) has focused on CO_2 quantification of stick-built construction. In that study, stick-built direct CO_2 emissions were quantified for single-family houses (1,600 ft^2) throughout all construction phases. The average CO_2 emissions for the production of a single-family house in that study has been quantified from observations and data collection of over 30 single-family houses. In order to compare emissions of pre-panelized and stick-built process, Mah's results are modified in this research and limited to the wood framing stage. Although insulation and vapour barrier are not included in the wood framing stage, they are considered in the assessments of both methods, since insulation is part of LBS' current pre-panelized process and thus accounts for a share of the utilities in the plant and other consumptions. Table 5 shows related stick-built emission elements and the associated CO_2 emissions for the wood framing stage. Mah (2011) has used the following formula for quantifying CO_2 emissions of construction activities.

$$CO_2\ (kg) = (\text{material trip numbers}) \times (\text{vehicle type}) \times (\text{distance})$$
$$+ (\text{labour trip numbers}) \times (\text{vehicle type}) \times (\text{distance})$$
$$+ (\text{duration}) \times (\text{equipment type})$$

(Equation 13)

The following is a numerical example:

$220\ CO_2\ [kg] = 1 \times 1.16\ [CO_2\ kg/km] \times 40\ [km] + 1 \times 0.34\ [CO_2\ kg/km] \times 40\ [km] + 4\ [hr] \times 40\ [kg/hr]$

Table 5: Stick-built evaluative stages

	Tasks	Du (hr)	Material Trips		Crew Trips		Equipment	Notes	CO_2 (kg)
			Q		Q				
1	Services								
	Main floor joists & subfloor package	2	1	5t truck					46.4
	Main floor joists & subfloor installation. "Capping"	8			2	0.5t truck	1 generator, 1 compressor		70.08
	Install propane basement heater		1	5t truck					46.4
		2	1	1t truck				winter operation, 1 x 5t truck for propane refill every 3 days (3 months)	716.24
2	Framing Main & Second Joists								
	Deliver first floor framing package -wall	1	0.5	5t truck					23.2
	Deliver first floor framing package -floor	1	0.5	5t truck					23.2
	Framing - main floor	16			8	0.5t truck	1 generator, 1 compressor		194.56
	Framing - main floor walls	16			8	0.5t truck	1 generator, 1 compressor		194.56
	Deliver second floor framing	1	0.5	5t truck					23.2

	package -floor								
	Deliver second floor framing package -wall	1	0.5	5t truck					23.2
3	Framing Second & Roof								
	Interior stairs delivery	2	1	1t truck w/ trailer					28
	Tarp basement stairs	1			1	0.5t truck			13.6
	Deliver roof package	2	1	5t truck					46.4
	Deliver roof trusses	2	1	5t truck					46.4
	Deliver Windows	2	1	3t truck					32.8
	Deliver additional lumber	2	1	3t truck					32.8
	Framing Second Floor walls	20			10	0.5t truck	1 generator, 1 compressor		243.2
	Framing roof	20			10	0.5t truck	1 generator, 1 compressor		243.2
	Crane the roof	2					20 t crane		11
	Crane the tub								11
	Crane the shower								11
	HVAC mark out	2			1	0.5t truck			13.6
	Frame Check	2			1	0.5t truck			13.6
4	Roofing								
	Temp walkways	2	1	5t truck					46.4
	Safety rails	2			1	van			9.2
	Repair Framing Deficiencies	2			1	0.5t truck			13.6
	Return un-used lumber	2			1	3t truck			32.8
	Site clean	2	1	5t truck					46.4
	Posts & Verandahs	8			1	0.5t truck	1 generator, 1 compressor		56.48
	City inspection #2 for framing				1	van			9.2
5	Other								
	Install Insulation & Vapour Barrier	8	1	1t van	1	0.5t truck			41.6
								CO_2 (kg) =	2396.1
								CO_2 (tons) =	2.40
							winter heating	CO_2(tons)=	3.51
								Total CO_2 per house (tons)=	5.91

4.8 Stick-built and pre-panelized carbon footprint comparison

The final results presented in Table 5 show that the production of a 1,600 ft^2 (148.64 m^2) single-family house emits 5.91 tons of CO_2 to the atmosphere using the stick-built construction method during the wood framing stage. This is 2.22 tons higher than the pre-panelized carbon footprint, which is 3.69 tons (Table 3). Figure 28 and Table 6 show a direct emission comparison for LBS' current process and Landmark's past stick-built process. Given this fact, the following conclusions are drawn for comparison.

- Compared to pre-panelized construction, the stick-built process emits nearly 37% more carbon to the atmosphere based on collected data in 2012.
- The winter heating average duration in the stick-built method is considered 25.58 days based on Landmark's historical data. This longer duration contributes significantly to total CO_2 emissions. The pre-panelized method emits 1.95 tons of carbon to the atmosphere for each house due to winter heating activity, which is 1.58 tons less than does the stick-built method.
- Compared to stick-built, pre-panelized construction releases a greater amount of CO_2 through utility consumption. Although this portion is almost 40% of total emissions, the panelized process still releases less CO_2 to the atmosphere due to its faster production.

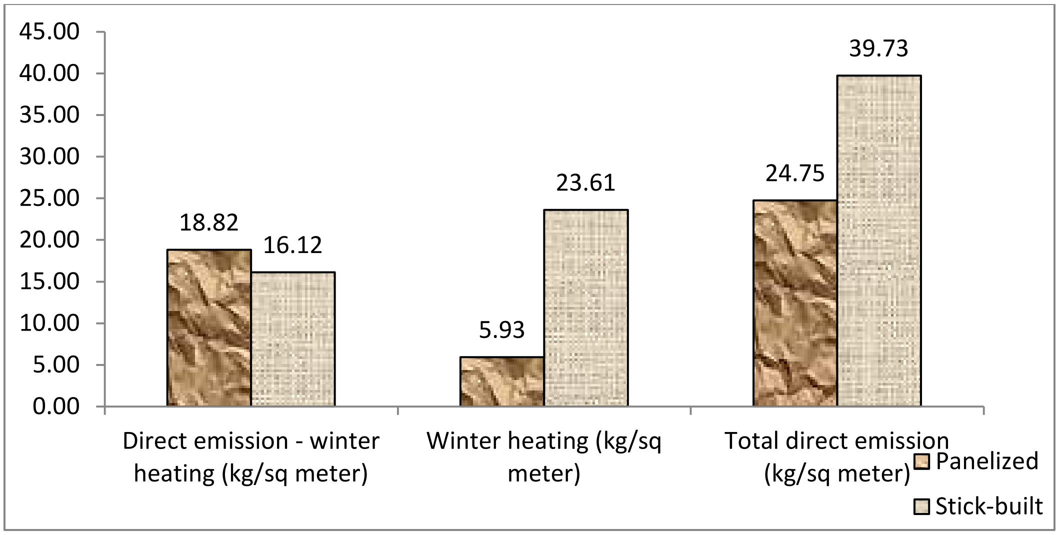

Figure 28 Direct emissions comparison

Table 6: Direct emissions comparison

	Direct emissions - winter heating (kg/m^2)	Winter heating (kg/m^2)	Total direct emissions (kg/m^2)	Winter heating duration (days)
Panelized	18.82	5.93	24.75	14.08
Stick-built	16.12	23.61	39.73	25.58
Difference	-2.7	+17.68	+14.98	+11.5

4.9 Optimum pre-panelized output compared to stick-built carbon footprint

CO_2 emitted due to different elements could be either constant or directly related to production (number of houses produced per year). For example, emissions due to natural gas usage are constant, since they do not change as production level changes. CO_2 emitted due to site workers' transportation fuel consumption, on the other hand, is directly related to production output since it changes linearly corresponding to production level. CO_2 emitted due to the portion of electricity used for running machinery in the factory is also correlated to production output. The portion of electricity, which is used for ventilation and lighting, is constant and does not change with changing production. Based on records, almost 80% of electricity is used for running machinery. It should also be noted that, if factory production increases, the change in the number of office staff will be negligible in terms of associated emissions. Table 7 summarizes the pre-panelized emission elements and their respective relationships with production output.

Table 7: Relationship of emission elements to production rate

Emission Element	**Function of Production**
Electricity usage	Constant (office); Linear (plant)
Natural gas usage	Constant
Plant equipment propane consumption	Variable (Linear)
Transportation + crane diesel consumption	Variable (Linear)
Lumber delivery fuel consumption	Variable (Linear)
D/W delivery fuel consumption	Variable (Linear)
LBS workers fuel consumption	Variable (Linear)
Site workers fuel consumption	Variable (Linear)
LBS office fuel consumption	Constant
Site managers fuel consumption	Variable (Linear)
Winter heating propane consumption	Variable (Linear)
Site generators fuel consumption	Variable (Linear)

Table 8 shows CO_2 emissions/house/year and associated emission elements. Based on Table 3 and Table 4, the total average constant emissions/year and total linear emissions/house/year would be:

$$\text{Total constant } CO_2 \text{ emissions per year}$$
$$= (0.2 \times \text{ electricity emission per year})$$
$$+ \text{Natural gas emissions per year}$$
$$+ \text{Office staff emissions per year}$$
$$= (0.2 \times 623.54) + 301.18 + 17.61 = 443.5 \text{ tons}$$

(Equation 14)

$$\text{Total linear } CO_2 \text{ emissions/house/year}$$
$$= (0.8 \times \text{ Electricity emissions per house})$$
$$+ \text{All variable emissions per house} = 3.014 \text{ tons}$$

(Equation 15)

Total linear CO_2 emissions/house/year is calculated based on data collected in 2012. It should be noted, though, that one year of data is not sufficient to quantify the benchmark of the pre-panelized process. Thus, linear CO_2 emissions/house/year represents the average CO_2 emissions for 2012. By carrying out further data collection in the future the benchmark of the process can be calculated more accurately. A ±10% variation for the results is assumed for pre-panelized and stick-built variable emissions. Also, a ±2% variation for the results is assumed for constant emissions. It is assumed that variable CO_2 emissions change linearly based on the production level, thus the variable CO_2 emission coefficient will not change by changing the production level in the future. In other words, variable emissions per house do not depend on the production; they depend only on the process. Based on historical data from Landmark, the average floor area of a single-family house is assumed to be 1,600 ft^2 (148.69 m^2). Observations show that the CO_2 emissions due to each activity are not completely sensitive to the floor area, and in fact depend primarily on the number of houses produced.

Table 8 CO_2 emissions/house/year and in associated emission elements

Emission Element	**Constant emissions/year (tons)**	**Variable emissions/ house/year (tons)**
Electricity usage	124.7083	0.7879
Natural gas usage	301.1849	-
Plant equipment propane consumption	-	0.0535
Transportation + crane diesel consumption	-	0.5511
Lumber delivery fuel consumption	-	0.1078
D/W delivery fuel consumption	-	0.0212
LBS plant workers' fuel consumption	-	0.1690
Site workers' fuel consumption	-	0.1701
LBS office staffs' fuel consumption	17.6105	-
Site managers' fuel consumption	-	0.0006
Winter heating propane consumption	-	0.9658
Site generators' fuel consumption	-	0.1871
Total	**443.5037**	**3.0144**

Hence, total CO_2 emissions based on annual production for pre-panelized and stick-built construction is calculated as in the following formula, where x represents the annual production (number of homes produced per year).

$$\text{Pre} - \text{panelized annual } CO_2 \text{emission}$$
$$= \text{Constant emissions per year}$$
$$+ (\text{Variable emissions} \times \text{Annual production})$$
$$= [443.50 \pm 2\% \text{ variation}] + [3.01 \pm 10\% \text{ variation}]\ x$$

(Equation 16)

$$\text{Stick} - \text{built annual } CO_2 \text{emissions} = [5.91 \pm 10\% \text{ variation}]x$$

(Equation 17)

The break-even points of the above equations show the range for minimum annual production of the pre-panelized process, based on the average CO_2 emission level in 2012, which will ensure better sustainability in the pre-panelized process compared to stick-built. Based on these equations, the annual pre-panelized production level should exceed the range of 141 to 167 houses per year in order to be considered a more sustainable process than stick-built process. Figure 29 shows the annual CO_2 emissions against annual production for both methods.

Minimum annual production of pre-panelized would be:

$$[5.91 \pm 10\% \text{ variation}]x$$
$$= 443.50 \pm 2\% \text{ variation}] + [3.01 \pm 10\% \text{ variation}]\ x \rightarrow x$$
$$= (141 \text{ to } 167) \text{ houses per year}$$

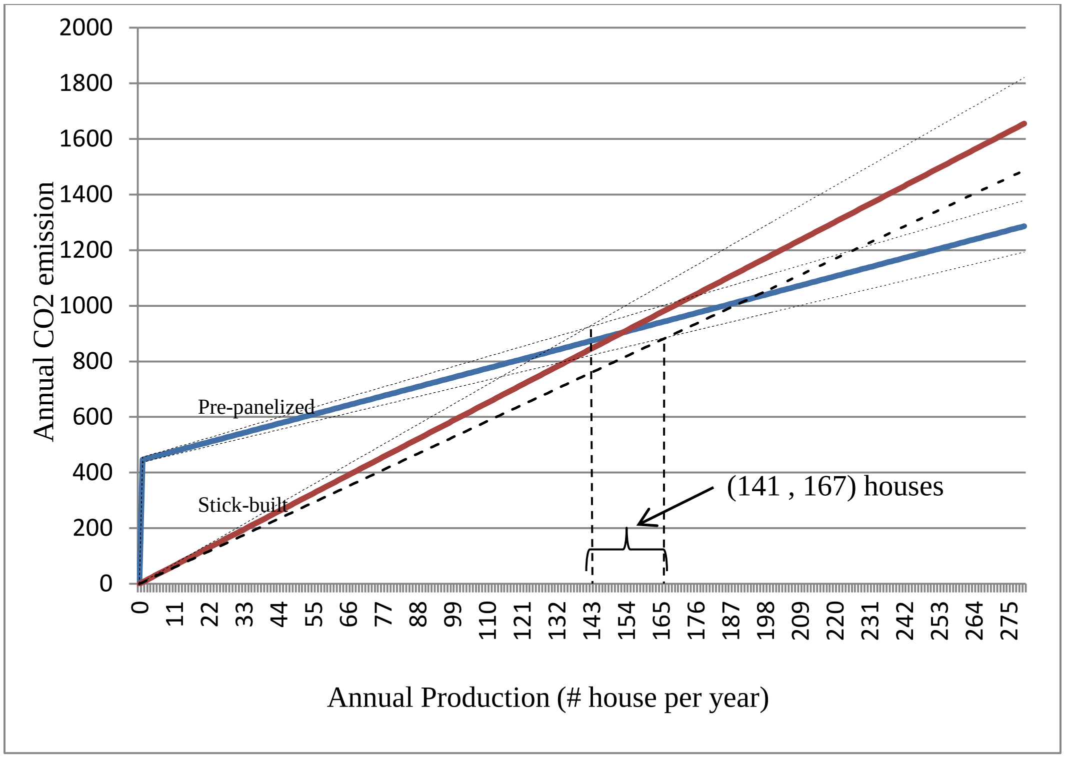

Figure 29 Pre-panelized vs. stick-built annual CO_2 emissions for 2012

By collecting more data in the future, mean and variance for the constant and variable emissions can be calculated. A confidence interval for the break-even points can be considered in the future based on additional data. To clarify, the range of 141 to 167 houses per year is derived from the 2012 data.

4.10 Material waste and indirect CO_2 emissions comparison

Wood waste in the current LBS process comprises two major categories. Factory waste is the result of panel production and site waste is mostly due to roofing and complementary work following assembly of the panels. Based on actual data, almost 75% of waste in the factory is wood waste and the remainder is non-recyclable materials. Site waste records show 50% of site waste to be wood. In this regard, research conducted by Mah and Al-Hussein (2008) has focused on quantifying material waste due to stick-built construction. Based on this study, construction of a 1,600 ft^2 (148.69 m^2) single-family house produces 974 kg of wood waste. Table 9 summarizes wood waste results for stick-built and pre-panelized methods. Based on the wood waste results, replacing the stick-built method with pre-panelized method has led to a 36% wood waste reduction in addition to the associated CO_2 emission reduction.

Table 9: CO_2 emissions comparison due to waste

Waste	Stick-built	Panelized	Difference	Difference (%)
Wood waste per house (kg)	974(1)	623	351	36%
Emissions per house (kg) due to wood waste	122	78	44	36%
Emissions per area (kg/m^2) due to wood waste	0.82	0.52	0.3	36%

4.11 Limitations and credibility of results

The results of this study are based on data collection in 2012. One year data reflect the benchmark of the LBS process in 2012. Thus, future data collection will increase the accuracy of and will provide a confidence interval for the results. The CO_2 emissions of each contributor (except natural gas, part of electricity and office staff) are more sensitive to the total number of produced houses and the process, while natural gas, (part of electricity and office staff emissions), is associated with almost constant numbers. Since CO_2 emissions are generally more sensitive to the number of produced units than to floor area, the average floor area of a single-family house in this study is considered to be 1,600 ft^2 (148.69 m^2) based on the production level in 2012. In general, the final results of this study are derived from data analysis based on the following assumptions;

1) Based on process observations, CO_2 emissions are not sensitive to floor area.
2) The average floor area of a single-family house is considered to be 1,600 ft^2 (148.69 m^2) based on the production level in 2012.
3) Collected data in 2012 is considered to represent stable values for the LBS process.

4.12 Chapter summary

Average monthly results show there is more room for improving the process of pre-panelized construction in terms of emissions and sustainability. Although the current LBS operations are more sustainable than Landmark's past stick-built process, certain considerations can lead to a further reduction in carbon footprint of the wood framing process. Faster production reduces the impact of constant emissions. Increasing the factory production by adding more working shifts or increasing working hours could also lead to decreased CO_2 emissions per house. Compared to the past stick-built process, pre-panelized construction leads to reduced CO_2 emissions if production output exceeds the range of 141 to 167 houses per year. The annual production of LBS in 2012, 654 homes, was much higher than this production threshold.

According to a report by the Canadian Solar Industry Association, Alberta has the most abundant solar energy resources in Canada (Canadian Solar

Industries Association, 2012). According to Figure 18, providing heat and electricity from a renewable source such as solar energy can further reduce LBS' CO_2 emissions by 39%.

Some of the barriers in applying new systems for using solar energy are the cost, variability of output, energy storage, and process integration (Environmental and Energy Study Institute, 2011). The upfront costs of applying new technologies are usually high, but in the long term the price could be justifiable. Another barrier is that, for industries with demand for 24-hour operations, using solar technologies can be a challenge. Coupling the application of solar panels with natural gas or electricity could be a solution to this obstacle. Using more insulation in the factory walls and reducing the factory temperature after working hours is also expected to help reduce utility consumption.

Finally, organizing the LBS fleet in terms of capacity would lead to less diesel consumption and associated CO_2 emissions. Also, reducing the duration gaps between different on-site construction activities in winter leads to less demand for field winter heating, which currently is a major contributor to carbon emissions.

Chapter 5: Conclusions

5.1 Research conclusion

The aim of this empirical research has been to quantify the environmental impact of pre-panelized construction, as well as to identify critical areas of possible process improvement. Landmark Building Solutions (LBS), a major building components manufacturer in Alberta, was the object of the case study presented in this thesis. Each step of LBS' production process, including material delivery, panel prefabrication in the plant, building component transportation to the site, and on-site erecting, was examined in order to estimate the direct CO_2 emissions from the process. Based on data analysis, a generic carbon footprint baseline based on application of the developed framework has been generated for LBS' operations which can be used as a benchmark for the pre-panelized construction method. Based on the contribution of each activity to the total CO_2 emissions of the pre-panelized process, critical areas have been identified and a list of suggestions for process improvement has been presented. Also, a simulation model which is capable of quantifying the benchmark of the pre-panelized process has been developed. The model developed is capable of specifying the benchmark of the pre-panelized process based on historical data in the future.

Data collection for the energy consumption of the fossil fuel records and wood waste records has been conducted from historical data of LBS and observation of the process. Based on the availability of data, different methods have been applied to quantify the CO_2 emissions of each section. Also, a simulation model has been developed which provides the benchmark CO_2 emissions of LBS' processes. Finally, a comparison between the stick-built and pre-panelized processes has been conducted, and the critical production level of the pre-panelized process has been specified for 2012. Since the study captures all the activities within the wood framing stage, the simulation model and the research framework can be applied for CO_2 assessment of the pre-panelized process in general.

According to the baseline of the LBS process in 2012, utilities, winter heating, and panel transportation contribute to a greater extent than other activities to the total CO_2 emissions of the LBS process. It is also concluded that, compared to the stick-built process, the pre-panelized process emits 37% less CO_2 due to operation and 36% less CO_2 due to wood waste. According to data collected in 2012, compared to the past stick-built process pre-panelized leads to a more sustainable method if the production level of the factory exceeds the range of 141 to 167 houses per year.

5.2 Research contributions

In this research, a comprehensive framework for data collection and GHG assessment of the pre-panelized construction process has been developed which assists panel manufacturers in quantifying the benchmark of their process and accordingly reducing their energy consumption and environmental impact. Also a simulation model has been generated which facilitates the long-term quantification of pre-panelized CO_2 emissions, and which is capable of predicting the likelihood of process CO_2 emissions in the long term.

5.3 Future research and recommendations

More data collection in the future will provide more accurate inputs for the framework and simulation model, which will lead to more accurate results for the benchmark of the pre-panelized process. The simulation model in this study can be developed in the future to evaluate and demonstrate the effect of design and size of the house on CO_2 emissions. Also, the research framework could be expanded in the future to assess the effect of changes in the process on CO_2 emissions of the pre-panelized construction process. Evaluating the effect of changes in the process on the profit level of the pre-panelized companies in the future could also be considered for future study.

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Appendix

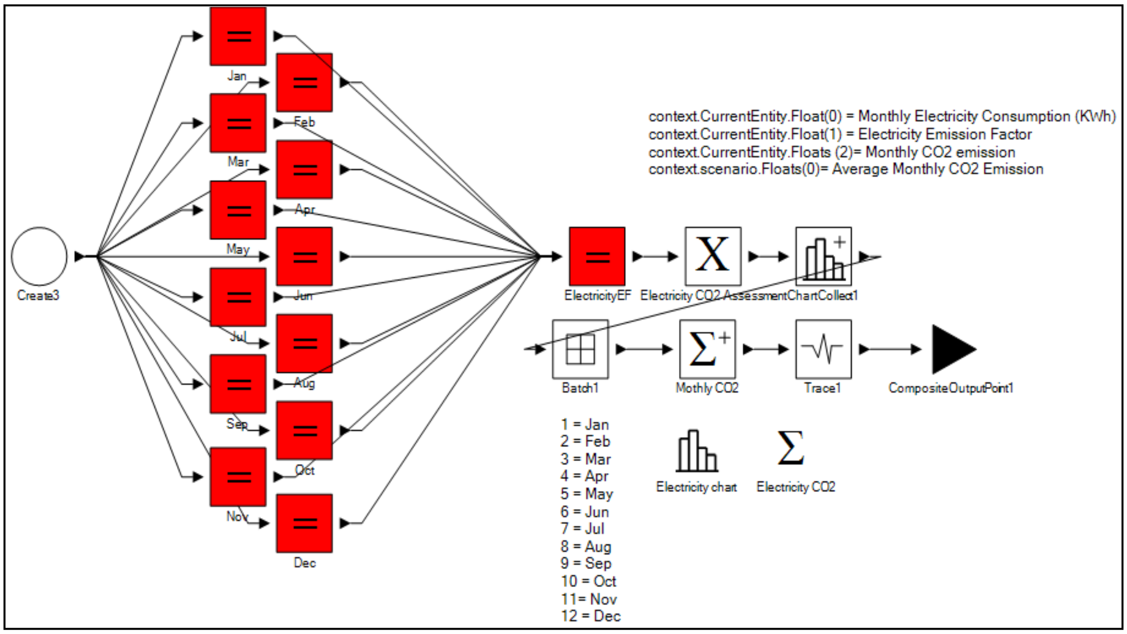

Figure 30 Simphony model for electricity

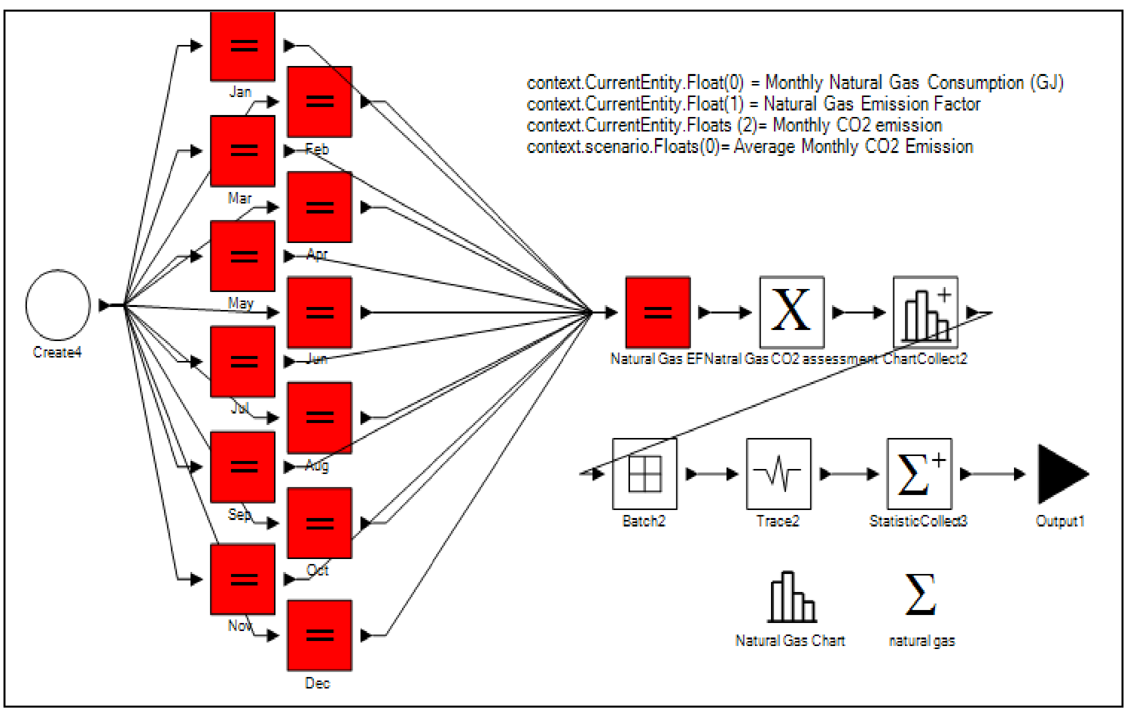

Figure 31 Simphony model for natural gas

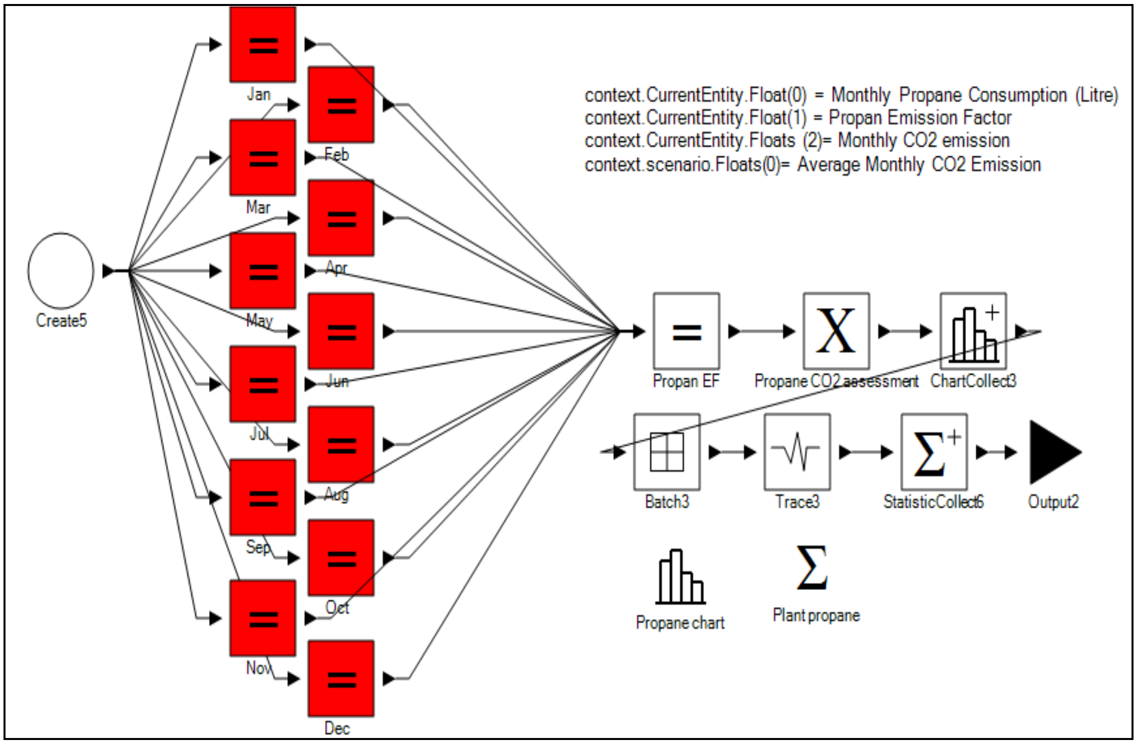

Figure 32 Simphony model for plant propane

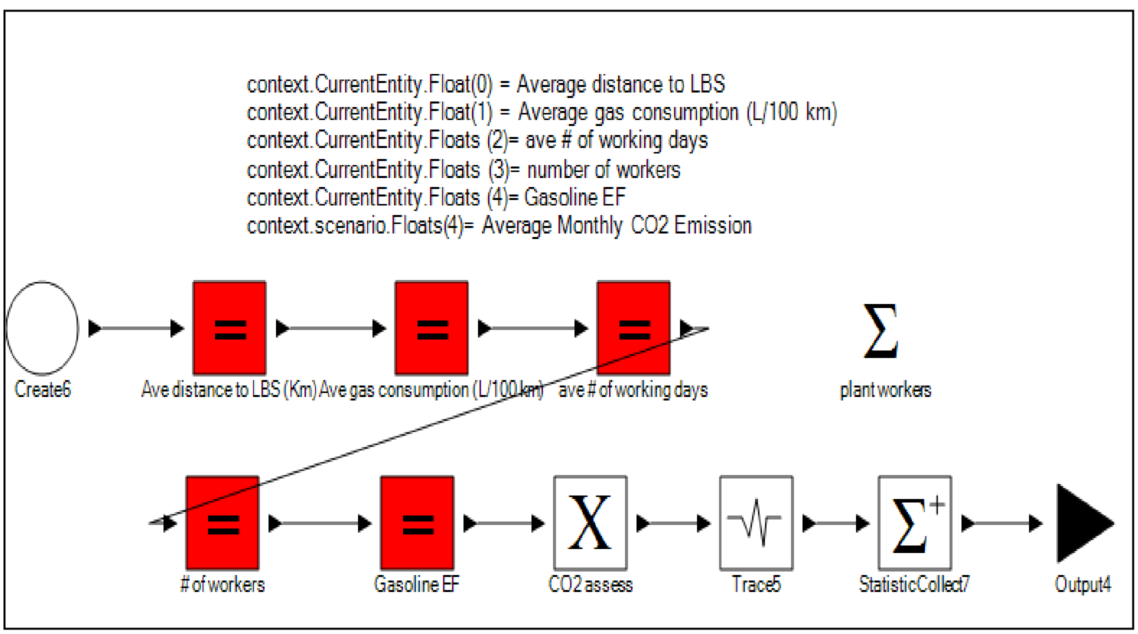

Figure 33 Simphony model for plant workers

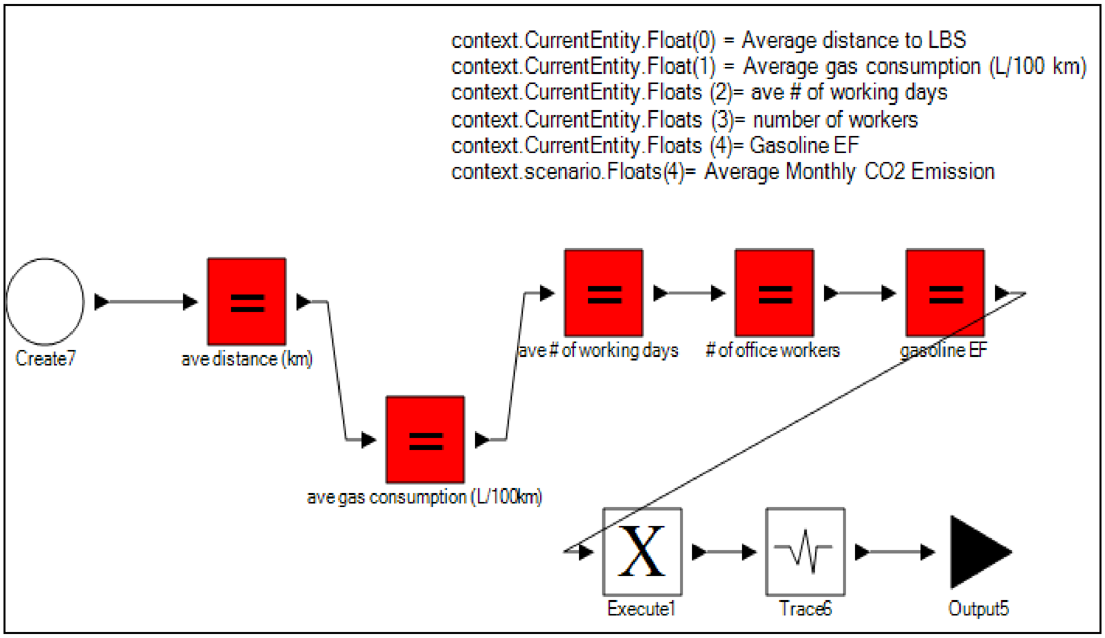

Figure 34 Simphony model for office workers

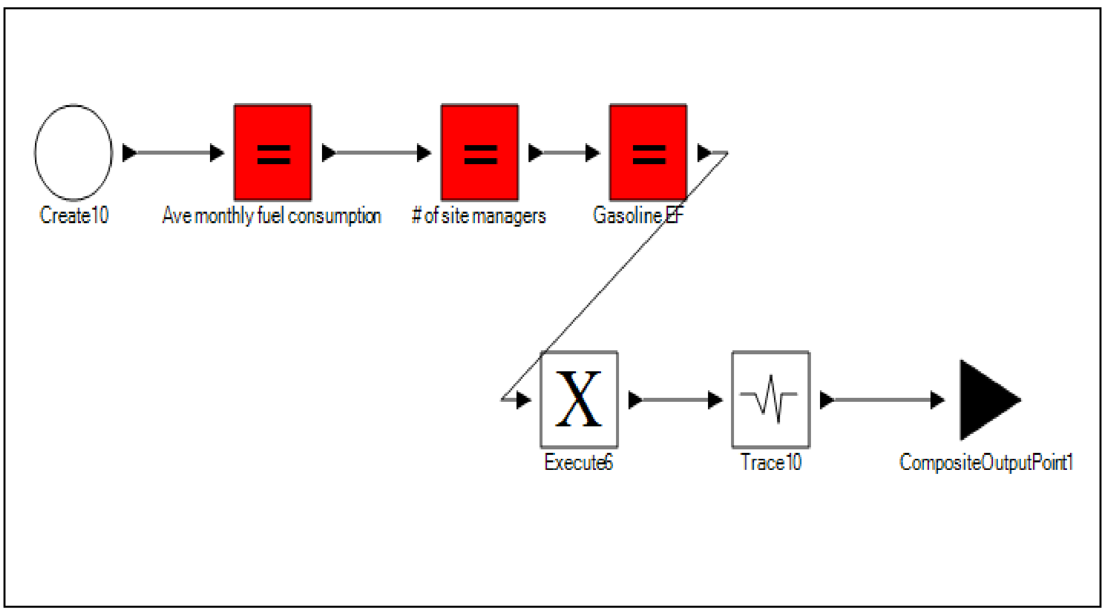

Figure 35 Simphony model for site managers

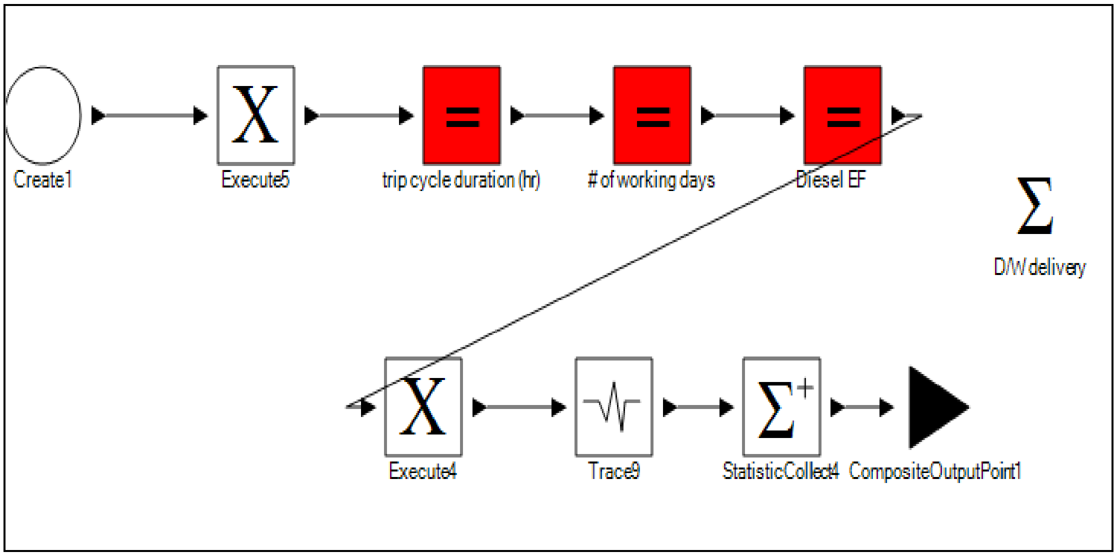

Figure 36 Simphony model for doors and windows delivery

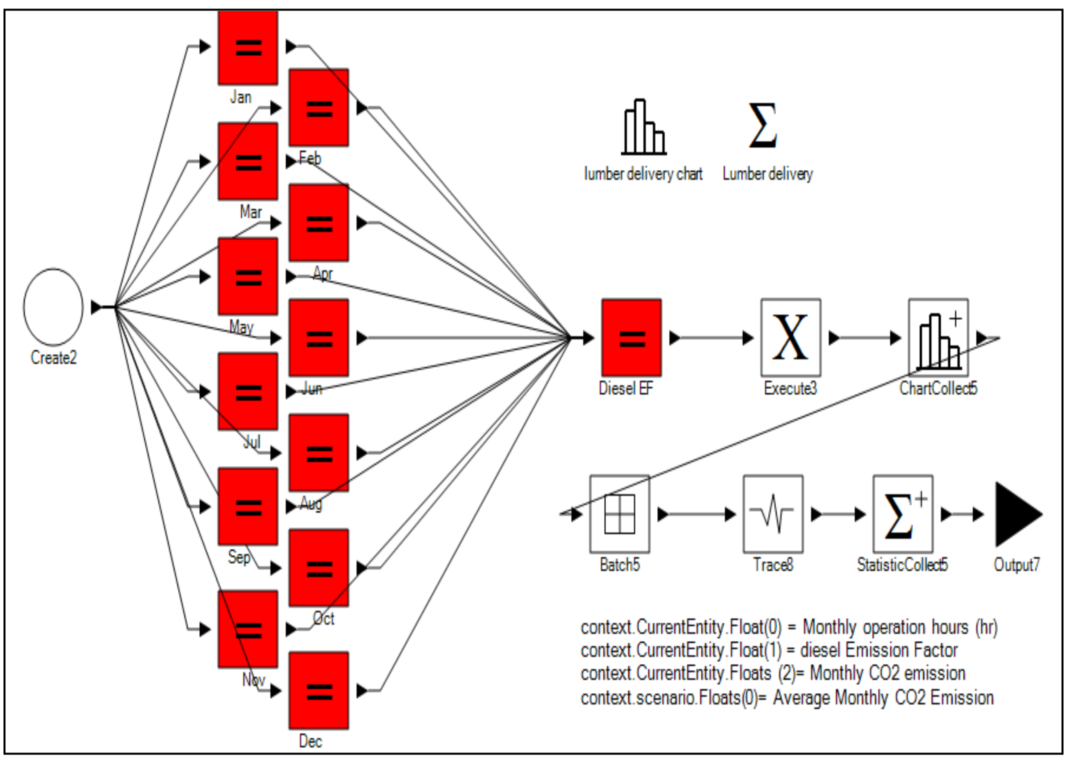

Figure 37 Simphony model for lumber delivery

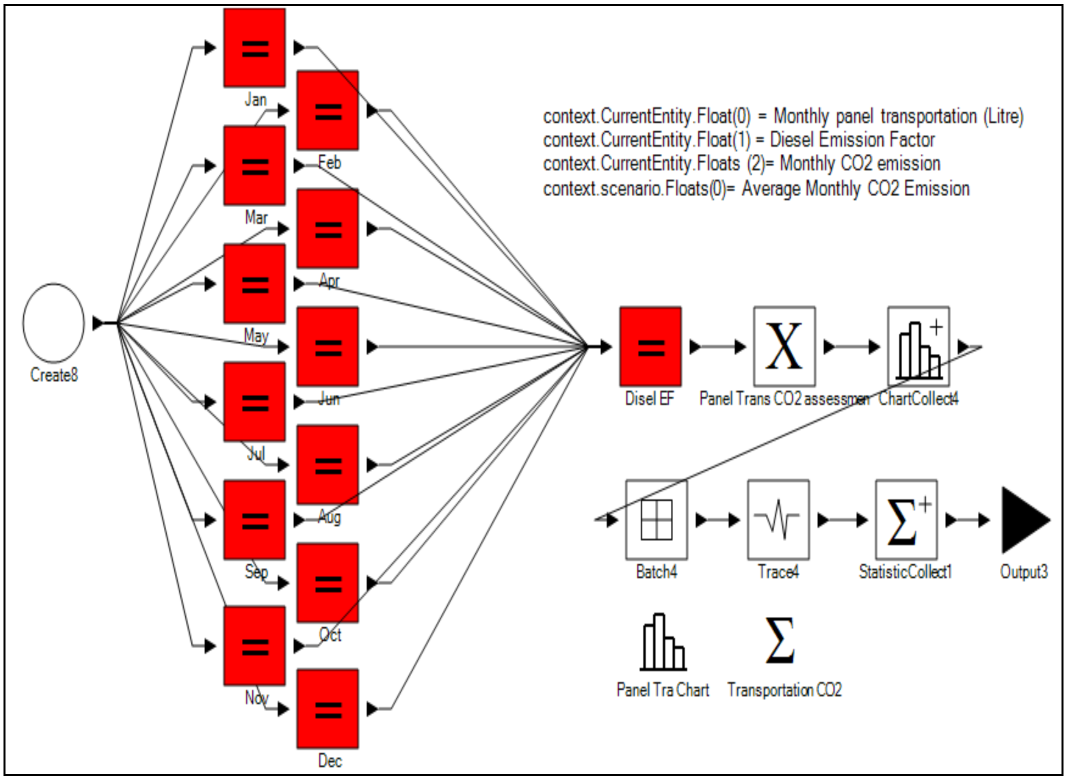

Figure 38 Simphony model for panel transportation

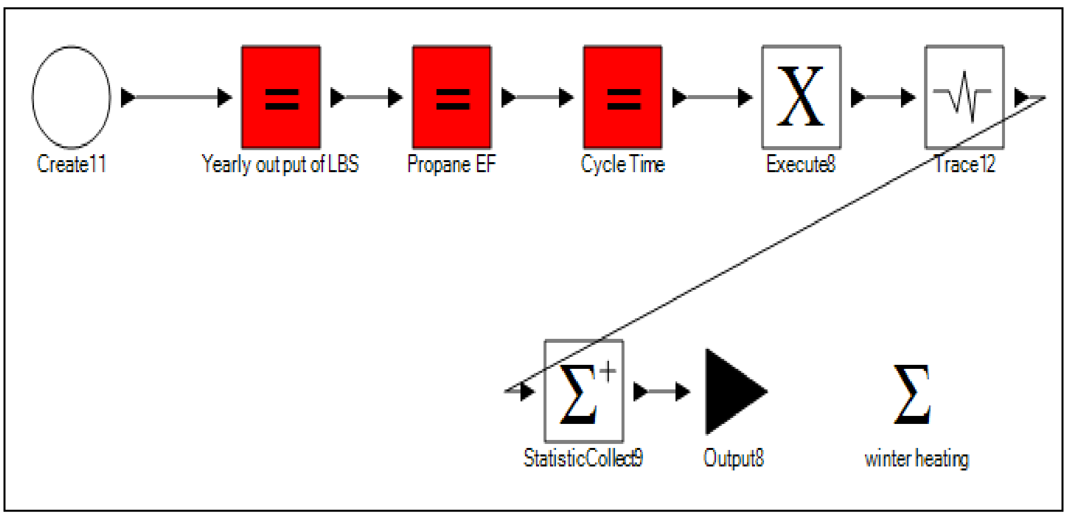

Figure 39 Simphony model for winter heating

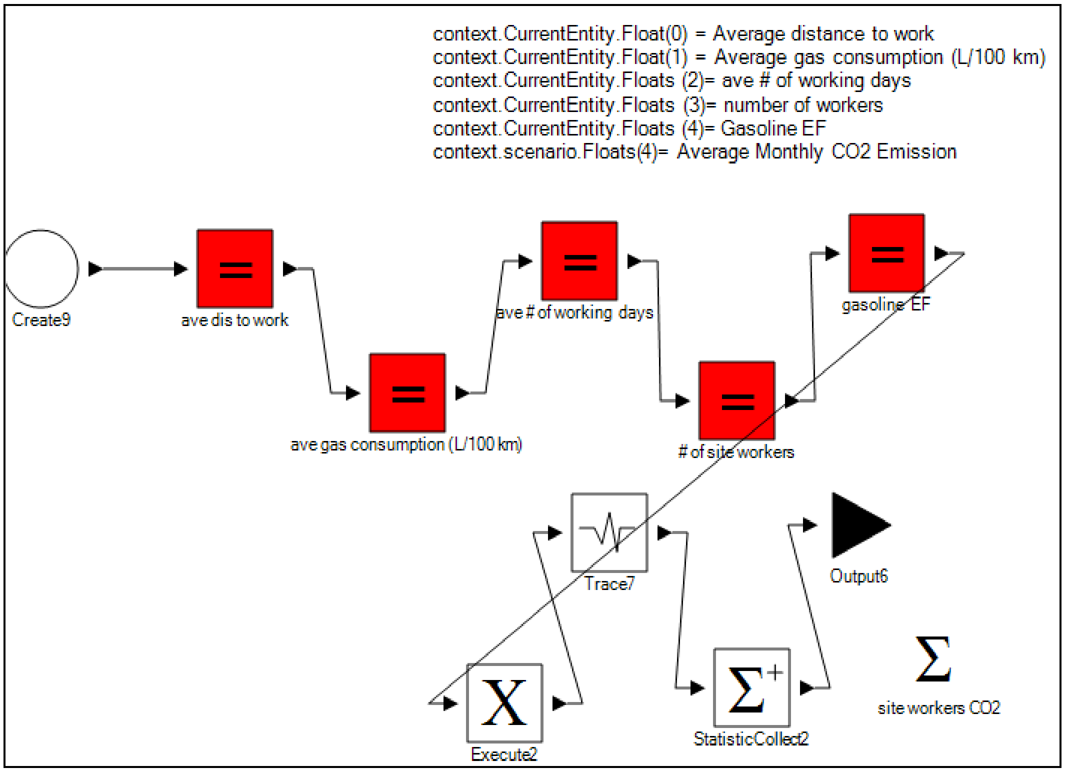

Figure 40 Simphony model for site workers

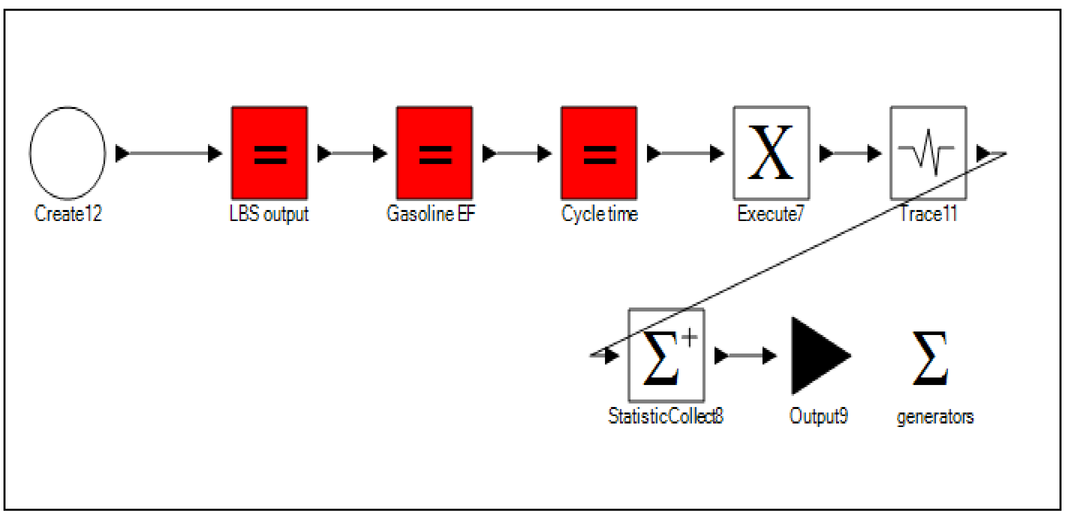

Figure 41 Simphony model for site generators