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AN INTEGRATED SIMULATION-BASED CONSTRUCTION CREW ALLOCATION AND TRADE-OFF WITH ENERGY AND CARBON FOOTPRINT

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ABSTRACT

On-site construction in winter consumes a considerable amount of energy and emits a significant volume of greenhouse gases, especially in cold regions. It has been reported that on-site winter heating accounts for 34% of carbon emissions of the framing phase for panelized house construction. In this paper, in order to quantify and analyze carbon emissions from on-site construction, the on-site panelized construction process is simulated in a combined discrete and continuous event simulation model based on which the possibility of reducing activity durations are investigated for the aim of reducing emissions. The integrated simulation methodology is demonstrated using case studies in Edmonton, Canada. Carbon emission which includes propane consumption for winter heating and diesel consumption for on-site mobile equipment and vehicles is calculated. Historical temperature data is analyzed to simulate weather behavior. Results show that on-site heating is the largest contributor to carbon emissions in panelized construction.

Keywords: panelized construction, on-site winter heating, carbon footprint, continuous-event simulation, discrete-event simulation

1. INTRODUCTION

Offsite construction, including modular and prefabricated, is becoming a more accepted and adopted approach in the construction industry to achieve better quality, less environmental impact and reduced time (Hong Xian et al. 2014). According to a study by Kawecki in 2010, the deployment of this method was increased by 48% between 1992 and 2002. Panelized construction accounts for the reduction of project duration by 63%, cost by 16%, and waste by 76% (The Panelized Process 2007). There is a belief that panelized construction method has many benefits compared with other construction methods; and some of which are: improved quality of end-products (i.e. wall assemblies, roofs, etc.) which can save energy, increase process velocity, and decrease the impact of bad weather on the overall construction process (The Panelized Process 2007). It also has a contribution to sustainability by the reduction of energy consumption and decreasing GHG emissions during the process of construction (Li et al. 2014). In addition, it is more cost efficient in terms of the need for on-site crew. Therefore, with increasing the cost of materials and skilled crew and in order to accelerate the construction phases, the demand of using panelized method is rapidly increasing (Friedman and Cammalleri 1992). A study by Friedman (1992) compared the construction expenses using panelized and conventional method for one single-family and concluded that there is no significant difference between them in terms of costs. More studies in this area indicate that saving costs of up to 6% would happen in some panelized methods (Ginter 1991). It reduces the CO_2 emissions comparing with on-site construction method by decreasing trips, the usage of equipment and also winter heating (Quality, Speed and Cost 2014).

The consumption of energy during the construction process is one of the most important impacts of a building on the environment (Palaniappan 2009). The construction phase of a building demands energy, material and other resources which imposes various forms of loads on the environment (Chinin et al. 2011). A study focused on pre-panelized construction method for its potential advantage of decreasing carbon footprint and energy consumption, found that savings of 30% in carbon emissions were achieved (Kawecki 2010). The pre-panelized method involves the assembly and fabrication of panels in plant, transportation of those panels to the construction site, and finally the erection of them on site. Thus, CO_2 emissions could be generated from the extract of materials, transporting them to the plant, fabrication of panels, moving them to the site and the construction process on site (Li et al. 2014). The distance between the plant and the construction site is the largest contributor of CO_2 emissions during the construction process (Kawecki 2010).

Not only climate change is today's environmental concern, but it will also impact the future generations. Different studies have given indications of global warming and a drastic ice melting in Polar Regions. “Canada's total GHG emissions in 2017 were 716 megatonnes of carbon dioxide equivalent (Mt CO_2 eq). The decrease in emissions since 2005 was primarily driven by reduced emissions from the electricity generation sector.” (Greenhouse gas emissions 2019).

In Canada, over 80 % of total national greenhouse gas emissions are associated with the production or consumption of fossil fuels for energy purposes." (Greenhouse gas emissions 2019). Findings proved the significant role of the gas in climate change and therefore the increasing level of warmth on the earth can gravely influence our future (The Carbon Dioxide Greenhouse Effect 2011). After examining different global energy scenarios in detail, the International Energy Agency (IEA) has indicated that global primary energy use is likely to increase by 36% between 2008 and 2035 (IEA 2010a; Dodoo 2011). These findings may heighten current concerns about energy security. Furthermore, fossil fuels are very likely to account for a significant share of future primary energy use, unless effective measures are implemented to promote sustainable energy systems in the global community (IEA 2011a).

Based on a study conducted by Suzuki et al. in 1995, it was found that the least energy consumption in construction (3 GJ/m2) is for wood structures. Another study by Gonzalez and Garcia in 2006 about CO_2 emission indicated that green materials selection and architecture design can significantly reduce the GHG impact on our environment. Miner et al. (2008) compared Energy consumption and CO_2 emissions of wood-framed buildings with non-wood-based buildings and found that wood-framed buildings needed 15-16% less energy for cooling and heating purposes in comparison with concrete-based buildings. In addition, this study found that greenhouse gas emission associated with wood-framed buildings were 20-50% lower compared to concrete-based buildings or steel-based building systems (Miner 2008). Mah (2007) also states that wood waste accounts for 60% of all waste in Canada.

Systems simulation has proven its effectiveness in analyzing various manufacturing operations (Wales and AbouRizk 1996). A study made by AbouRizk et al. in 2011 states that the dynamic and complex characteristics of construction operations make it a challenge to properly estimate project duration, resource utilization, and job conditions, since they highly depend on external factors such as weather conditions, holidays, resource availability, unscheduled breakdowns, etc. In order to create a simulation model of a housing project it is required from the simulation expert to be aware of the uniqueness of each project and knowledgeable of (a) the logic and sequence of the operation; (b) simulation algorithm and techniques; and (c) software tools and applications (AbouRizk et al. 2011). Simulation is defined by AbouRizk (2011) as *"the science of modeling a construction production system and experimenting with the resulting model on a computer"*. The history of simulation software refers back to 1955-1960; namely "the period of search", and mainly took five main stages through the next 30 years to evolve, as described by Nance, 1995. Halpin (1973) was the first one to introduce the concept of simulation to construction processes and operations. That concept came after Teicholz (1963) who adapted link-node methodology to earth moving operations, and Gaarslev (1969) who compared the results of queuing theory and simulation when studying simple two and three cycle construction systems. Esfahani (2013) compared the simulation engine developed by Hajjar and AbouRizk (1996), which can get the distributions and run the model for several times, with other methods such as MS Excel spreadsheet which can also estimate the amount of CO_2 emissions but only for one year and concluded that using Simphony.NET is more accurate.

Simulation of process and construction operations has been extensively used in the past decades. For example, Mohsen et al. (2008) used Simphony.NET simulation engine to investigate the onsite assembly of the modules used to build five dormitory buildings. Altaf et al. (2015) developed an online simulation-based and RFID production control system in a panelized construction factory. Also, Ismail et al. (2017) adopted a simulation technique to support construction project planning. RazaviAlavi et al. (2017) developed a simulation model to optimize construction site layout planning. Moreover, Golabchi et al. (2018) proposed an integrated approach to design and evaluate construction safety and labor productivity using simulation modeling and visualization. Mohsen et al. (2018) utilized discrete-event simulation to model the floor operations at a cabinet manufacturing facility.

2. METHODOLOGY

The scope of this study focuses on using different simulation techniques (discrete and continuous event simulation methods) for the purpose of quantifying and investigating the possibility of minimizing the CO_2 emissions associated with the transportation of materials from the plant to the construction site, on-site construction equipment, and on-site winter heating taking place during the panelized construction of single family houses, using the General Purpose Template GPT in a simulation engine developed by Hajjar and AbouRizk (1996) at the University of Alberta.

The actual input data of this study is collected from 200 panelized housing projects performed recently by Landmark Group of Builders in Edmonton, Alberta between 2011 and 2013. The construction process involved six main stages: (1) date-to-field - framing start, (2) framing start – siding start, (3) siding start – drywall boarding start, (4) drywall boarding start-stage1 finishing start, (5) stage1 finishing start – carpet finish, and (6) carpet finish – possession date. The obtained data (also considered as historical data) involves the precise start and finish dates and durations of each of the mentioned stages. For the detailed activity durations, transportation needs, and resources required to perform those activities, the researchers considered experts' knowledge to obtain the most likely (mode), or minimum and maximum (uniform) durations, number of vehicle trips and their types, and special resources. Actual construction operations as performed in the field are stochastic by nature (AbouRizk et al. 2011). Consequently, the researchers made advantage of the available historical data to (1) validate the simulation model, and (2) investigate the gaps between the expert and actual data, which result from the weather conditions, unavailability of different resources, poor documentation and abstraction of the project details, and other unknown reasons. As previously mentioned, there are many sources of CO_2 emissions during the construction phase. Figure 1 summarizes the research methodology followed to conduct this study. The previously mentioned simulation engine is used to simulate the panelized single family house construction process, temperature variation throughout the year, as well as the associated CO_2 emissions with such process.

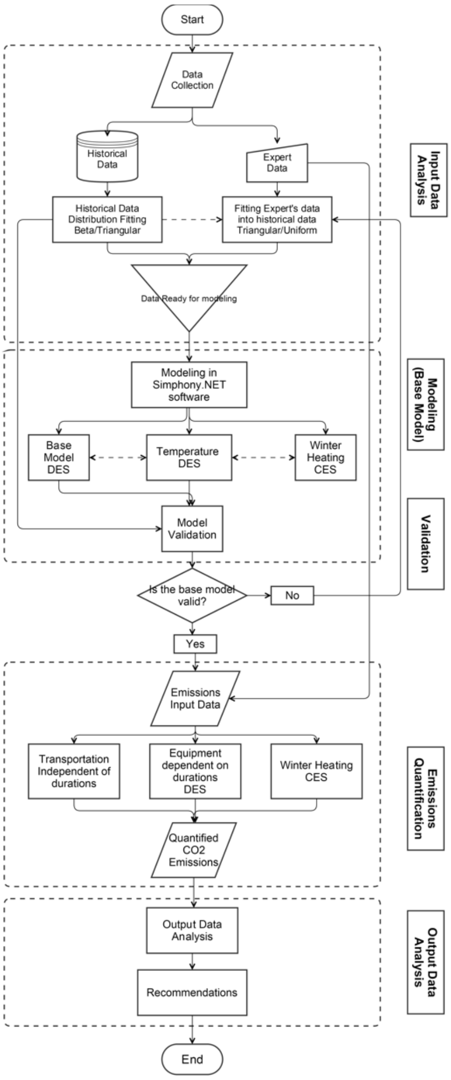


Figure 1: Research methodology

3. DATA COLLECTION AND ANALYSIS

The collection and analysis of input data are considered as a major task in simulation, where one of the first steps in that task is to hypothesize a distributional form for the input data (Banks 1996). A study conducted by AbouRizk in 1992 states two types of data experienced by the random process simulationist; (a) collected observations from historical data (as demonstrated in Table 1); and (b) judgement of a person knowledgeable about the process, where there are no available observations. A study by AbouRizk in 1990 also focused on choosing appropriate distribution as an input for the model. It states that if the data records are unavailable, the modeller must rely on intellectual advice of an expert for modeling. Experts usually specify a uniform distribution or triangular distribution for a data. Choosing a proper distribution is a very important part of the modeling (AbouRizk and Halpin 1990).

Similarly, in the present study, there are two types of data collected to serve this project; historical data mentioned previously, and experts' knowledge data collected from relevant researchers and industrial partners. The historical data is generalized to six main stages of house construction, but neither includes detailed information about resources nor sub-activity durations. This data is accurate and represents real durations for each of the six stages mentioned before. It also includes start and finish dates of each stage. The research team took a good advantage of those dates to investigate and compare between the time it takes to build a house in both summer and winter; in other words snow versus no-snow seasons. In Alberta, it is assumed that snow season starts on the first of October and ends by the end of March, and followed by no-snow season commencing from the first of April till the end of September. Data was split and analyzed on that basis. The historical data was used in that project in three main ways; (a) to validate the output data from the base simulation model, since it mimics the actual construction process; (b) to help fit experts' data input into proper probability distributions; and (c) to fill the gaps that result from the divergence between real construction process data reflecting its stochastic nature, and theoretical data obtained from experts, which is most likely deterministic. In his book "Discrete-Event System Simulation" (1996), Jerry Banks stated that the validation process should be achieved in an iterative process of calibrating the simulated model and comparing it against the actual system behavior, and also manipulating the gaps between the two, to improve the simulated model. This point will be explained later in the following paragraph. As mentioned earlier, the dynamic and complex characteristics of construction operations make it a challenge to properly estimate project duration, resource utilization, and job conditions (AbouRizk 2011). According to AbouRizk (1992), the beta distribution has proven its advantage in modeling the activity durations for most of the simulation applications in construction. Contrarily, the Johnson and Pearson systems do not recommend the beta distribution (AbouRizk 1992). In this study two software applications were used to fit the historical data into proper distributions; (a) @Risk software, and (b) simulation engine (Hajjar and AbouRizk 1996). The researchers compared the results and found great similarities between both software platforms in terms of fitted distributions.

Most of the data was fitted into either beta of triangular distributions. Reviewing the historical data, it was observed that the panelized construction process takes an average of 150 working days to construct a house in winter. Consequently, it was hard for the research group to collect field data in the limited time of the project, and the only possible way to obtain detailed activity durations was the use of other relevant studies, or experts' knowledge input. This type of data was given as one deterministic value, which is regarded as the mode. In order to give the model a stochastic behavior, each activity duration was inherited a low and ultimate value with the same ratio of the historical data distribution it lies within. Consequently, the parameters of a triangular distribution can be determined (low, ultimate, and mode).

Table 1: Fitted distributions of historical data using @Risk and simulation engine (Hajjar and AbouRizk 1996)

	From	To	Oct1-Mar 31	Apr 1-Sep 30
1	Date-to-field	Framing Start	Beta (8.9852,3.9139,1.897,28.366)	Triangular (5,33.4,58)
2	Framing Start	Siding Start	Beta (1.06,3.6,8,55)	Beta (0.973,3.291,8.5,50.5)
3	Siding Start	Drywall Boarding Start	Beta (2.905,5.658,10,40)	Beta (1.1157,3.048,12,72)
4	Drywall Boarding Start	Finishing Stage1 Start	Beta (3.24,5.0697,12,35)	Triangular (15,15,33)
5	Finishing Stage1 Start	Carpet Finish	Beta (1.537,8.416,20,45)	Triangular (14,26,29)
6	Carpet Finish	Possession Stage	Triangular (18,22,99)	Triangular (18,26,35)

4. MODEL

By adopting historical data, experts' knowledge data, and similar previous studies, a simulation model was created to mimic the real panelized construction process for the purpose of quantifying the CO_2 emissions associated with construction. The modeling process in this study consists of two major components; (a) base model which represents the construction process in detail; and (b) quantification of emissions resulting from the operations in the base model.

4.1. Base Model

The General Purpose Template GPT in the simulation engine was selected to simulate the construction process through a DES model. The time unit was selected to be in actual dates, so that the research team can investigate the duration and CO_2 emissions with respect to different project start dates. From the historical data, it was observed that each activity-duration varies according to the time of the year it was commenced. Figure A-3 in the appendix demonstrates the panelized construction process. After running the model for 30 run counts, the results have shown that the project duration varies between 133 and 156 days according to the date of the year the project started. On the other side, the propane gas tank consumption/refill rate was modelled as a CES, where the outside temperature controls whether or not the heater is turned on. The refill rate of the propane tank is controlled by the consumption rate of propane gas. A five-ton truck refills the propane tank when the amount of propane gas drops to 10 Liters. Figure A-6, A-7, and A-8 demonstrate the combined DES and CES models of the propane tank rate of consumption/refill and the refilling truck cycle.

4.2. Emissions Quantification

The purpose of this study is to investigate the carbon dioxide emissions resulting from the panelized construction operation, focusing on three main emission types: (1) crew and material transportation emissions, (2) on-site equipment emissions, and (3) winter heating emissions. The first type relies on how many vehicle trips are performed back and forth between the construction site and the manufacturing plant to transport either the crew or materials. This type of emission is easy to quantify since it only depends on the amount of labour and materials to transport, and distance to travel. It was found from relevant studies that the average distance travelled by the different types of vehicles is equal to 40 Kilometers. The second type is split into two sub-categories; duration-dependent, and duration-independent. The duration-dependent equipment emissions are those affected by the task duration, such as the compressor and generator. In this case, the shorter the activity duration, the lower the carbon dioxide emissions will be. Unlikely, the duration-independent equipment performs its tasks based on the amount of work to be done, regardless of how fast or intensive the laborers are, such as the crane and the excavator. The equations for emission quantification of those two types of emissions were obtained from a study by Li et al. (2014) at the University of Alberta. The third emission component involves winter heating. On-site winter heating is mandatory in cold regions such as Alberta, whenever the outside temperature reaches below −5˚C. The reason behind winter heating is to keep the construction crew, as well as the building materials and equipment safe and warm during severe weather conditions in winter. Once the heater is installed, it becomes available for heating whenever heating is needed (temperature is below −5˚C). The consumption rate of the propane-gas-filled heater is 100.1 liters per day, where its capacity is 300 liters (Mah 2007). A five-ton truck is responsible for refilling the heater tank when it reaches 10 liters. Each Liter of propane produces 1.51 Kilograms of CO_2 (Mah 2007). CO_2 emissions resulting from winter heating are encountered from two main sources; (1) propane gas consumed for heating, and (2) truck trips for heater tank refilling. It is obvious that winter heating is controlled by one factor, which is outside temperature. A recent study by Li (2014) defines the daily minimum temperature by the polynomial Equation below, which has been concluded by the analysis of historical temperature data from the city of Edmonton online database.

$$y=9*10^{-11}x^{5}-5*10^{-08}x^{4}+10^{-6}x^{3}+0.0022x^{2}-0.101x-10.393 \qquad (1)$$

This polynomial equation was manipulated by a discrete-event simulation DES model (Figure A-4) in the simulation engine to mimic actual weather data (Figure A-1 and A-2), and be used to study the behavior of the CO_2 emissions resulting from on-site winter heating, and thus, quantify those emissions over the course of the project. Using the daily temperature variation generated, the consumption rate of propane gas can be quantified by a continuous-event simulation CES model, and thus the number of truck trips can also be determined, making it trivial to compute the amount of CO_2 emissions of winter heating.

From experts' judgement input, a 1000-Gallon truck full of propane takes approximately 30 minutes to unload. This means that the rate of fill is equal to (1000 Gal*24 hours/day*60 minutes/hour)/30 minutes = 4,800 Gal/day. 1 US gallon is equivalent to 3.78541 liters. The rate of fill in terms of Liters per day will be (4,800 Gal*3.78541 liters/Gal) per day = 18,169.968 Liters/day (300 liters of propane are equivalent to 79 Gallons). Figure 2 demonstrates the continuous model that represents the in-flow rate of filling propane gas into the tank, and the out-flow rate of the propane gas consumed in winter heating. Table 2 and Table 3 summarize the emissions resulting from material transportation based on a 40-Km travel distance and on-site equipment, respectively.The consumption rate of propane is directly dependent on the outside temperature. The emission rate resulting from winter heating is 62.7 Kilograms of CO_2/million BTU/hour (Mah 2007). It is observed from Figure 2 that propane gas consumption happens only if the outside temperature is below −5°C.

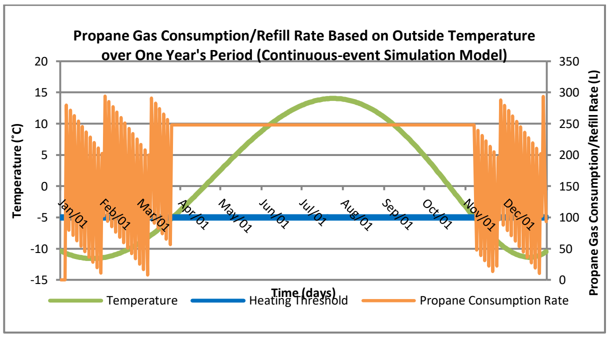


Figure 2: Weather and propane consumption data generated by the simulation engine

Based on the historical data analysis, activity durations in summer differ from those in winter. Accordingly, the results from the simulation model show a similar divergent behavior of project durations depending on whether the project commenced in summer, or in winter, or in between. The results show that the project duration varies between 133 days (starting in January) and 158 days (starting in December). In order to reduce the carbon footprint resulting from the construction process, the duration of the process itself should be reduced. However, before any embellishments have been considered, the base model was validated using the available historical data as described in the following section.

Table 1: Emissions resulting from material transportation (duration-independent) based on a travel distance of 40 Km

Vehicle Type	Emission Kg/Km	Total Emission Kg/ 1 Vehicle trip (40 Km)
van	0.23	9.2
0.5t	0.34	13.6
1.0t	0.7	28
3.0t	0.82	32.8
5t	1.16	46.4
concrete pump	1.16	46.4
concrete mixer	1.16	46.4

Table 2: Emissions resulting from on-site equipment (duration-dependent) per unit time

Equipment	kg/hr	Kg/day (8hr/day)
spreader	40	320
generator	2.68	21.44
excavator/backhoe	40	320
crane	16	128
compressor	2.68	21.44
Bobcat	28.63	229.04

5. BASE MODEL VALIDATION

Although simulation is a beneficial way for solving problems, the users are always concerned whether or not the outcome is correct. Thus, decision makers validate models in order to determine their accuracy (Sargent 2007). Schlesinger et al. (1979) defined model validation as "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model". According to the study by Balci and Sargent in 1982a, 1982b and 1984b, because of the availability of historical data, the best approach for validation is creating the simulation model deploying a sample from distributions of historical data.

Validation by comparing simulated data to historical data is one powerful technique according to Sargent (2003). Consequently, before any output data analysis has been assessed, the base model has been validated through creating a simple validation model (consisting of the six main stages previously mentioned) and fitting historical data into task durations, and comparing the base model to the output results from the historical data being simulated (Figure 3).

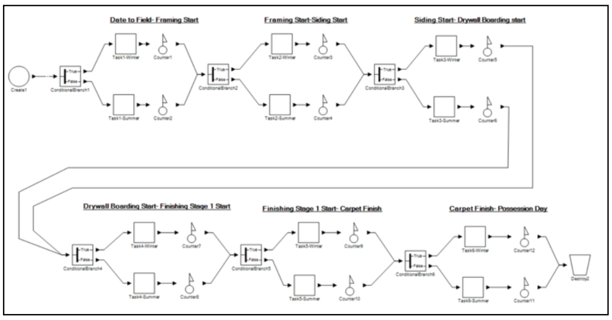


Figure 3. Validation through the simulation of fitted historical data

Fortunately, the project duration of the validation model was almost typical to the simulation model at the same time of the year. It took 140 to 157 days to finish the project according to the validation model. By comparing those results with the results from the base model simulation, it was observed that both models are very similar, thus, the base model can be considered as a reliable model.

6. RESULTS, DISCUSSION AND CONCLUSION

A basic simulation model is generated and integrated, which can compute three types of emissions accompanied with panelized single family house construction operation, including transportation, on-site mobile equipment, and winter heating emissions. This model is an abstraction of a real life problem, and in search of more accurate results, and thus further details and factors should be put into consideration in the future. Other emission types may be added to this model. In the modeling phase, comparing historical data to experts' judgement data, the research team found some time gaps, where no work has been done, or some sub-activities were not documented, or other factors impacted the work progress. It is of a great importance to quantify the impacts of uncertainty variables which affect the project schedule, and consequently the project cost (Wales and AbouRizk 1996).

6.1. Results

The output data was obtained from the simulation engine by running the simulation model several times starting at each month of the year to investigate different respective project emission scenarios. This section discusses the results and behavior of each of the three types of emission. As mentioned earlier, transportation emissions are fixed regardless of the project duration or weather conditions. Those emissions only depend on the travelling distance between the manufacturing plant and construction site, and amount of material to be hauled (i.e. number of trips). The traveling distance is, unfortunately, hard to change. It was observed from the results that the first stage of the construction process accounts for 49% of the total transportation emissions and decreases gradually as the project progresses, as shown in Figure 4. Emissions resulting from on-site equipment depend primarily on its hourly rate of emission and activity durations, specifically the generators and compressors. It was noticed from this study that emissions resulting from equipment are directly proportional to activity durations. It was also observed that the crane and the excavator are responsible for an outstanding amount of emissions compared with other equipment (Figure 5).

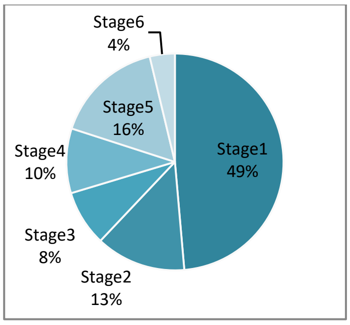


Figure 4. Transportation emissions at different stages of the project (duration-independent)

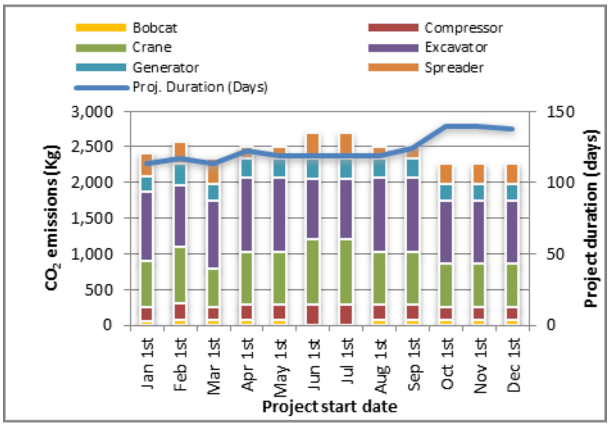


Figure 5. On-site equipment emissions based on project start date (duration-dependent)

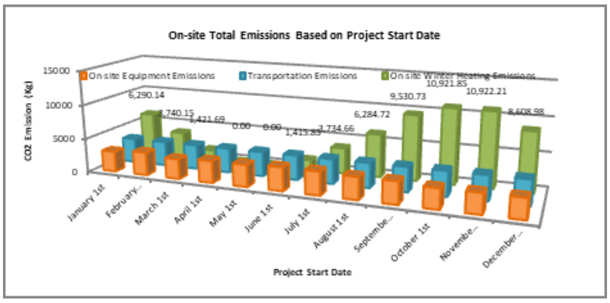


Figure 6. Different types of CO_2 emissions associated with different project start dates

From the simulation engine statistics collection analysis, winter heating was found to be biggest component of CO_2 emission throughout the construction process. It relies primarily on the time of the year at which the project started, and also on the overall project duration. A project starting between October and November accounts for an overall CO_2 emission of 11,000 kilograms, but if the same project started between April and May, the associated CO_2 emission will be reduced to zero kilograms (Figure 6).

6.2. Embellishments and Recommendations

The goal of a successful project is to perform the job in minimum duration (for cost saving) with maximum resource utilization (for maximum productivity) (AbouRizk 2011). From the ecological point of view, for the sake of reducing CO_2 emissions resulting from the construction process according to this study, it is advisable to either mitigate (if possible) on-site construction activities taking place between September and December, or reduce project durations by increasing the crew size at some specific activities. Some activities were observed to have significantly longer durations than others such as framing, siding, drywall boarding and taping, and painting. Those activities were triggered in this part of the study to reduce their respective durations. It is worth mentioning that this study is an abstraction of a real life problem, and that this assumption might not be feasible if other conditions (such as space confinement, resource availability, job quality, etc.) were put in consideration. It is assumed that doubling the crew size (labor-intensive) would reduce the corresponding activity duration by the half. It is also assumed that the transportation needs would remain the same, since the crew was originally assigned a large van for transportation.

As a result of the mentioned embellishment, the project duration has been reduced to a minimum of 113 days (starting in March) and a maximum of 140 days (starting in October). This embellishment accounts for the reduction of the construction process by 19 days, which is equivalent to 13% of the overall original project duration. Regarding the corresponding CO_2 emissions, 21.5% of the on-site equipment emissions can be reduced, 9.6% of winter heating emissions were also cut, and an overall reduction of 10% could be achieved due to this embellishment, as shown in Table 3. Regarding transportation emissions, the project duration does not imply any positive effect on it, as it was previously defined as duration-independent. A study made by Mah in 2007 at the University of Alberta states that switching vehicles from diesel to propane can reduce up to 30% of the CO_2 emissions produced during construction. Future studies may be conducted to investigate the impact of changing the fuel type of different vehicle types on their carbon footprint.

Table 3. Output analysis of the embellishment results

Type of Emission	Base Model	Embellishment	Reduction (Days)	Reduction (%)
On-site Equipment Emissions (Kg)	3131.9	2457.3	674.6	0.22
Transportation Emissions (Kg)	3602.4	3602.4	0	0
On-site Winter Heating Emissions (Kg)	5239.2	4734.8	504.4	0.1
Total Emissions (Kg)	11973.6	10794.5	1179.1	0.10
Proj. Duration (Days)	142.4	123.6	18.8	0.13

As a future recommendation, further studies should be conducted to investigate the possibility of the reduction of the carbon footprint resulting from the panelized construction method of single family houses in cold regions. The research team also recommends the collection of more accurate input data that can explain the significant gaps between actual and theoretical data. Triggering those gaps can give a better image of the possible solutions for reducing the whole project duration, thus reducing its carbon footprint. It is also advisable to conduct a future study which focuses on the optimization between winter heating cost (which accounts for maximum CO_2 emission) and the cost of reducing construction activities within winter months (September through December).

APPENDIX

A. Simulation Model

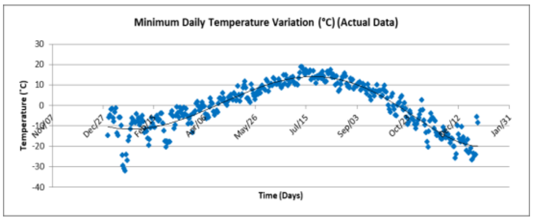


Figure A−1: Historical temperature data obtained from the city of Edmonton online database

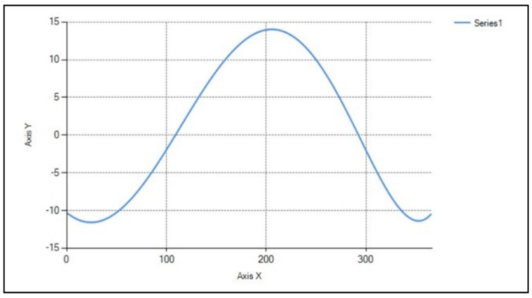


Figure A−2: Minimum daily temperature generated by the simulation engine using a 5th degree polynomial equation

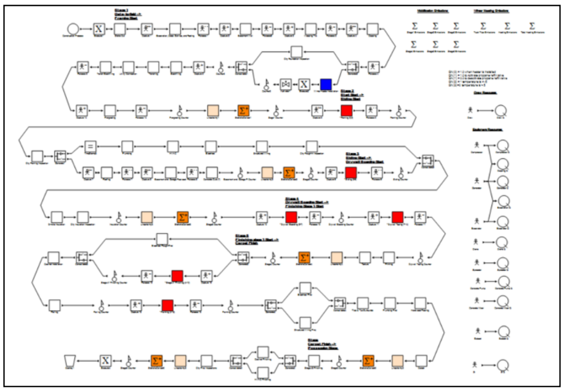


Figure A−3: DES model of the panelized construction process, duration in days

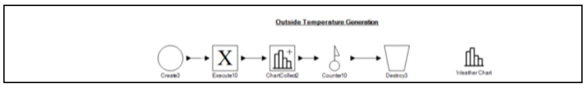


Figure A−4: DES model generating temperature variation over one year’s period

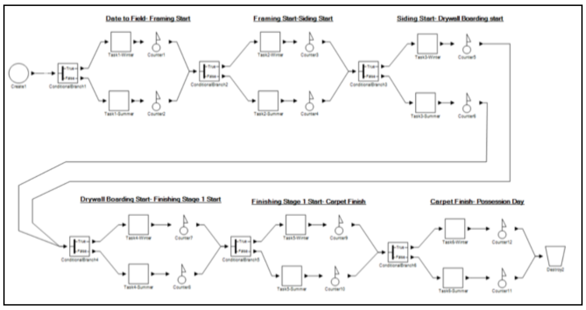


Figure A−5: Base model validation through simulation of historical data (summer and winter) through a discrete-event simulation model

B. Simulation Engine Charts

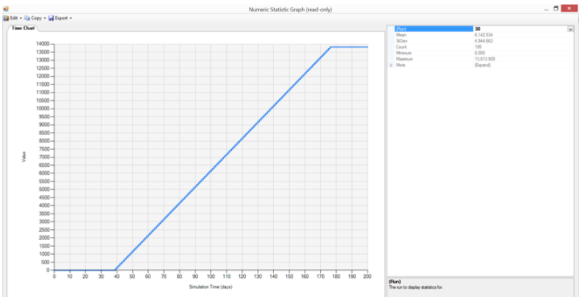


Figure B−1: Propane stock (liters) if construction started in October 1st

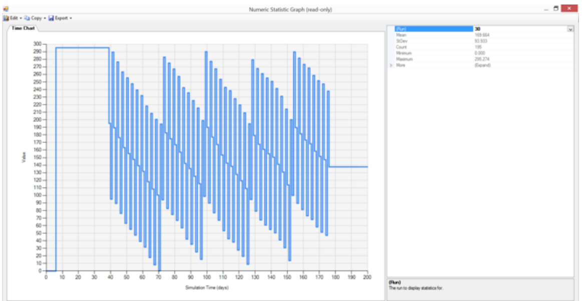


Figure B−2: Propane Tank consumption/refill rate if construction started in October 1st

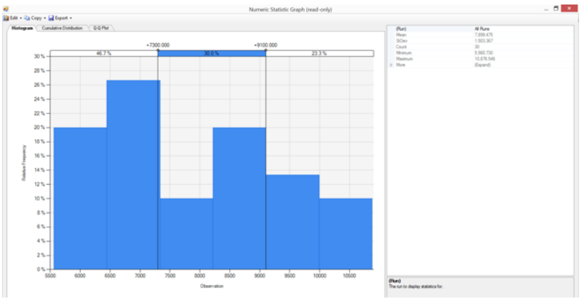


Figure B−3: Propane Emissions if project started on October 1st

C. CO_2 Emissions Model (Combined DES and CES)

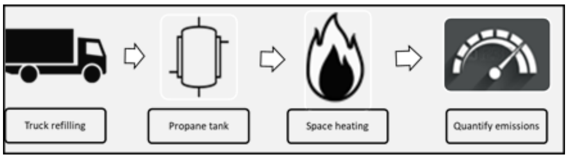


Figure C−1: Conceptual model of the CES simulation model

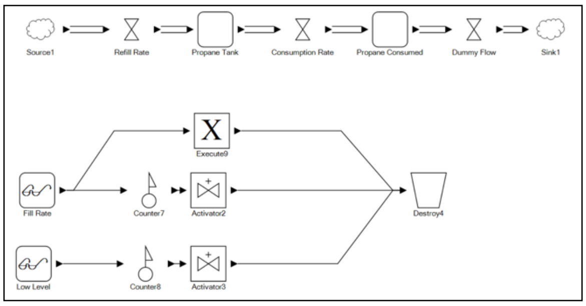


Figure C−2: CES model of the consumption/refill rate of propane tank

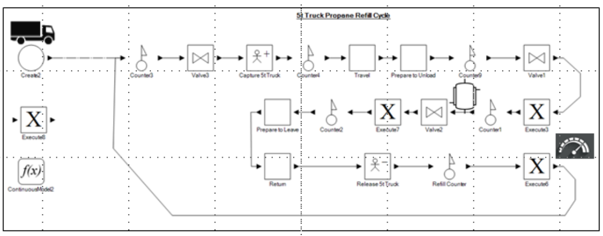
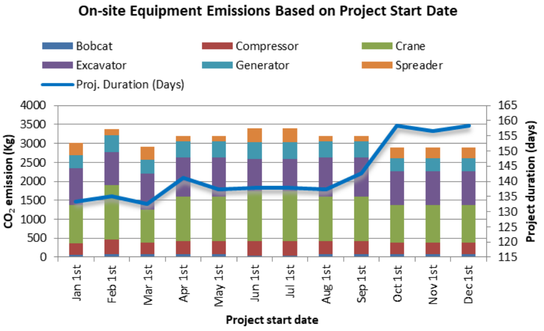
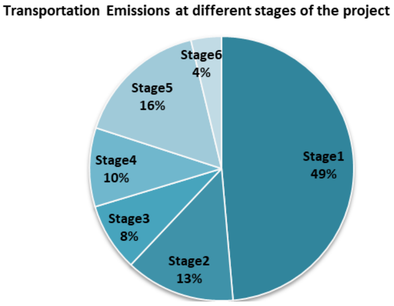
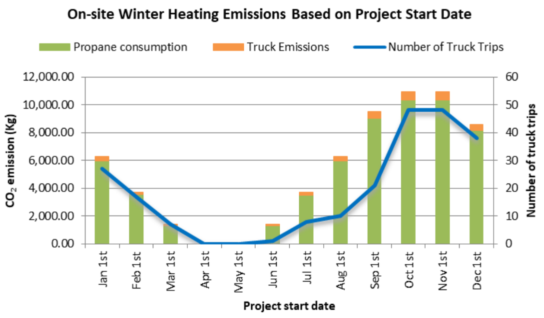


Figure C−3: DES model of the refilling truck cycle

D. Base Model Results

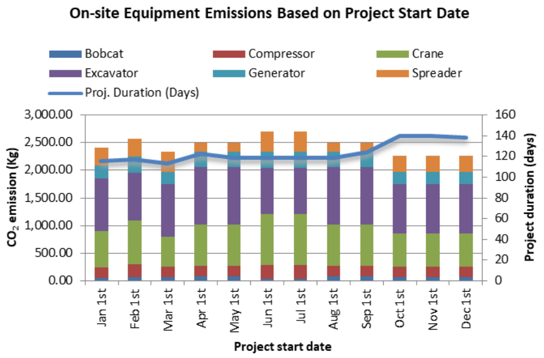


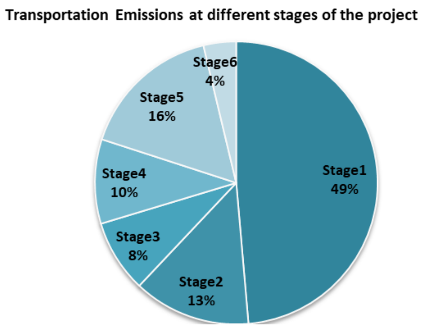


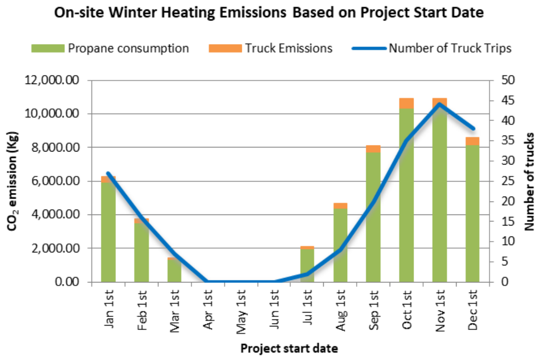


E. Embellished Model Results

(13% reduction in project duration, 21.5% reduction in equipment emissions, and 10% in winter heating emissions)







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