Integrating Simulation and Emission Models for Equipment Cost Analysis in Earthmoving Operations: Application Framework

by

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Abstract

The construction industry is one of the major economic sectors that exert substantial influence on the state of the environment. There has been extensive research endeavors to develop methods and materials that are intended to turn this industry more cost-efficient while mitigating negative environmental impacts. However, the industry still creates a significant burden on the environment and further research and development on sustainability is desired by the construction industry and the society at large. This research aims to develop a methodology to address the immediate need for improving the sustainability performance of construction projects. To do so, this thesis develops an application framework that integrates simulation and emission models for equipment cost analysis in earthmoving operations. The application framework is based on the concepts of lean and green construction and the quantitative analytical models based on field measurements by Lewis (2009). Ultimately, the application framework represents a guideline that clearly defines the required information and system logic in order to develop simulation models that will select appropriate construction equipment considering greenhouse emissions and productivity performance simultaneously. The thesis also includes a case study in earthwork construction to demonstrate the practical application and effectiveness of the proposed methodology.

Preface

This thesis is an original work by Nicolas Diaz Hernandez.

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CHAPTER 1: INTRODUCTION

1.1 Background

Modern construction industry is credited to be one of the largest employers and leading industries of the Canadian economy. However, it is also attributed to be among the largest consumers of natural resources and perceived as a business that faces significant management obstacles. One of these obstacles is the proper management of fleet equipment.

A fleet of heavy equipment is an essential part of the site transport system and vital to successful business operations of a heavy construction contractor. Management of fleets is a significant undertaking in construction projects as it has great implications in achieving completion of projects in a timely manner. Additionally, operation and maintenance costs of construction equipment make up a considerable amount of the total project cost. Likewise, the extensive use of fleet equipment partly accounts for the fact that the construction sector is a substantial producer of pollutants.

Due to the growing attention that public and private organizations pay to the implementation of sustainable practices, construction managers are compelled to consider non-financial criteria when purchasing, operating, and maintaining a machine, and replacing it. Unfortunately, there are limited studies that provide construction managers with a guideline on achieving sustainable goals in construction projects.

In order to assist members of the construction industry accomplish sustainable goals, this thesis will develop an application framework based on the application of environmental assessment and the use of simulation models. The framework will help fleet managers maximize the cost-effectiveness of equipment while reducing their environmental impacts based on Lewis' construction equipment emission measurement and evaluation (Lewis, 2009).

1.2 Motivation

Currently construction companies only consider financial elements when operating large construction equipment, while green aspects have been largely neglected in the analysis of cost efficiency (Ahn & Pearce, 2007; Koushi & Kartam, 2004; Ohno & Ohno,1998). As effective management of construction equipment is a critical aspect of thriving organizations, there is a need to measure greenhouse gas emissions due to construction activities and link this sustainable performance indicator to analyses of construction productivity.

In order to improve the sustainable performance of construction projects, it is necessary to evaluate the greenhouse gas emissions of construction equipment as a cost factor. Although there are studies attempting to measure greenhouse gas emission during construction operations, a methodology that links the measurements to operations has yet to be established. Therefore, an application framework that links emissions measurements to construction activities is desired.

1.3 Objectives

This research aims to develop an application framework that provides construction managers with a guideline to obtain sustainable operation, while maximizing the cost-effectiveness of equipment. In particular, the framework will consider environmental and mechanical factors through the integration of simulation models and the environmental assessment performed by Lewis (2009). Ultimately, the framework will assist construction managers in selecting the most efficient equipment combinations for their company's objectives.

The work conducted in this research has the following objectives:

1. Develop a framework that clearly outlines the required information and logic in order to develop simulation models that can assists construction managers in integrating environmental targets into fleet combinations.

2. Formalize the integration of simulation and emission models to assess fleet combinations in construction processes.

3. Quantify greenhouse gas emissions as a cost factor so it can be used as an environmental performance indicator in heavy equipment utilization.

1.4 Thesis Organization

This thesis is divided into five chapters to discuss the research methodologies.

Chapter 1 describes the motivation and research objective of this study.

Chapter 2 contains a summary of the literature review for similar studies. There are three main areas in which academic papers have been reviewed: sustainability in the construction industry, lean construction, and the role of equipment in the construction industry.

Chapter 3 Presents the proposed framework and discusses the integration of simulation models into environmental assessments, such as Lewis' work (2009).

Chapter 4 discusses the application of the proposed framework on common construction processes and gives a step-by-step demonstration of its use.

Chapter 5 exhibits a case study to illustrate the application of the proposed framework.

Chapter 6 gives a conclusion, outlines limitations of the work and discusses future studies.

CHAPTER 2: Literature Review

2.1 Introduction

There is a considerable amount of information related to sustainability and green construction, especially on the positive impact that it has on communities' living standards. This literature review starts with an introduction to sustainability, lean thinking, waste in the construction industry, green construction, modeling equipment operations, followed by a description of simulation models and earthwork equipment in the construction industry. The chapter concludes with a detailed description of Michael Lewis' work in fuel use and emission rate fuel.

2.2 Sustainability

The term sustainability began to shape our world in the 1970s, during a time that was marked by the rapid growth of the human population and escalated consumption of natural resources. These concerns led the United Nations (UN) to discuss possible solutions to balance the decay of the environment and the growth of the world's poor without affecting their well-being. As a result, the UN's 1972 Stockholm Conference produced *Our Common Future* report, and the term of sustainability first appeared (Portney, 2015).

The Brundtland Report (1987) defined sustainability as "The development that meets the needs of the present without compromising the ability of future generations to meet their own needs (p.16)." This new concept has been challenging traditional business models and transforming the political world by encouraging communities and individuals to understand the social, economic, and environmental impacts they have with their surroundings (Poveda, 2017).

Over the years, the concept of sustainability has been adapted to different meanings in various fields of study, such as biodiversity, economics and more. Consequently, the adaptation into other fields has negatively impacted the meaning of the original concept. Today, modern sustainability goes beyond the environmental aspects of resolving natural resources' collapse and the rapid growth of the human population. The developed concept of sustainability acknowledges that societies cannot create systems that balance the basic human needs and the environment. Instead, sustainability must consider the principles of futurity, economy, and public transportation to create "sustainable communities" (Mitchell et al., 1995).

The modern concept of sustainability was subsequently refined through the Triple Bottom Line (TBL), a framework proposed by John Elkington in 1998 to measure the performance of measuring corporate institutions in America (Elkington, 1998). In this framework, Elkington (1998) proposed three dimensions of performance, essential to the success of organizations: “social (people), environmental (planet) and financial (profit).” These dimensions focused on the economic and environmental integration of a business with its social environment, as it is essential for sustainable performance.

TBL, alongside sustainability, showcases how an organization can be truly sustainable when proper importance is given to the three P’s: People, Planet and Profits. Socially, a business must have the social capital to attract customers and employees while having the ability to operate. Environmentally, organizations need to operate in ways that mitigate adverse impacts on the environment in which they operate. Economically, organizations need to pursue work that generates profits. Therefore, organizations that proportionally target all three of these elements, as shown in Figure 2-1, achieve sustainable development.

Figure 2-1. Illustration of the Triple Bottom Line of Sustainability. Reprinted from *Be Green Business And Mean It* by Cerilli, L, 2016, getmetrics.

A focal point of modern sustainability is the relevance that needs to be given to each pillar. For example, if a greater focus is given to the economy's pillar, there will be greater use of natural resources that will create more substantial amounts of contamination to the environment while it broadens the inequality between the social classes of a nation. Nonetheless, if a greater focus is given to the society's pillar, it will take many financial and natural resources to upgrade the quality of life of those in the lower classes of society. Although, if greater importance is given to preserving the environment, it will be difficult for the economy to generate sufficient income to satisfy today's population (Epstein and Rejc, 2014). As a result, organizations need to identify and understand the sustainability measurement that is well balanced to give equal significance to each aspect of modern sustainability.

2.3 Lean Thinking

As communities and organizations are more concerned over environmental degradation, competition between companies in terms of cost, price, efficiency, and even social responsibility has risen. This rise in the competition leads many private organizations to integrate the lean philosophy into their operations.

Lean thinking is a business methodology derived from the pioneering work of Kenichi Ohno and Izumi Ohno (1998) in developing the Toyota Production System (TPS). The objective of this methodology is to deliver more benefits to society and individuals by providing them with the necessary service, at the right time and in the right amount, at a just price, and by making use of the minimum amount of materials, equipment, space, work and time required to provide quality services (Paksoy et al., 2019).

The key to lean thinking is the elimination of waste that does not provide any value to the final service or product. Ohno and Ohno (1998) identified six sources of waste that are detrimental to the productivity of an organization:

1. Waste from Overproduction: Production of quantity greater than required or than necessary, which, on many occasions, is very difficult to identify.

2. Waste from Rejects: Unsatisfactory work may be caused through a broad range of reasons such as poor design, lack of planning, poor teamwork and production, among others.

3. Waste from Transportation: Every movement of equipment and materials should have a purpose for items being moved as it incurs a cost. Excessive handling, the use of faulty equipment and bad pathway conditions are the common cause of this waste.

4. Waste in Processing: Includes the waste of intellect spent in jobs beyond the requirements of the client, which can be related to unused employee creativity by not making the most use of employees’ skills and knowledge.

5. Waste from Materials: Resulted from lack of resource planning or uncertainty on the estimation of quantities.

6. Waste from Waiting: Related to turn-around time or cycle time of any process in the project. It includes waiting for material, information, equipment, and tools, among others.

Ohno and Ohno (1998) believed that by developing processes free from waste and non-value adding activities, companies would be able to increase their efficiency and competitiveness. However, for processes and products to become lean, they needed to follow these five principles (Alves et al.,2019):

1. Value: Specifying a value from the client's perspective. Hence, waste will be anything that does not add value to the project or clients' criteria.

2. Stream Value: Use of proper assessments and planning tools to determine inefficiencies in an end-to-end process.

3. Flow: Have a clear vision of construction activities leading to a reduction of idling.

4. Pull system: Generating exact work required by a client.

5. Perfection: Delivering correctly what the client wants at a reasonable price.

2.4 Waste in Construction Industry

The impact of the construction industry on the environment is considered among the largest and most influential contributors to its depletion. The waste produced by this industry does not only involve the construction phase of a project but includes the production of materials, transportation and the demolition of the project at the end of its life cycle (Richardson, 2013).

The production of waste in construction sites is often related to inadequate storage and protection of materials, poor site control, purchase of excess materials, lack of training and poor stock control (Ferguson,1995). Nevertheless, research on this subject has increased to improve all stages of waste minimization in construction, such as land use, replenishment of natural resources, construction methods, transport network and economic and social interaction of projects to communities (Richardson, 2013; Ferguson 1995).

The modern construction industry impacts the environment in three fronts: depletion of natural resources, pollution, and waste production. According to Roodman et al. (1995), the construction industry consumed nearly 40% of all raw materials available and usable worldwide. Shen and Tam (2002) argued that pollution from this industry comes from the manufacturing of materials, transportation, and the extensive use of energy resources that emitted large quantities of greenhouse gases, such as CO2. At the same time, Koushi and Kartam (2004) argued that the most significant waste in the construction industry in terms of volume and waste came from activities such as excavation, site clearance, demolition and building renovations.

Another type of waste seen in the construction industry does not involve the environment. Instead, it follows the principles of Lean Thinking. In a lean environment, there are three types of waste Muri, Mura and Muda (Pieńkowski, 2014):

- Mura: Refer to variations in work output concerning volume and quantity in a production system. Although mura is not waste per se, it leads to Muri and Muda.

- Muri: Refers to unreasonable demands on processes and employees, in the form of inadequate training or high workload.

- Muda: Indicates waste in resources in non-value-adding activities or activities that create waste.

Table 2-1. Comparison between waste in non-lean environments and waste in the construction industry.

Waste in Non-Lean Environments	Waste in Construction
-Waste due to overproduction. -Waste due to stocktaking. - Waste due to transportation. -Waste due to the system / process itself. -Waste due to defective products. -Waste due to waiting periods. -Waste due to movement.	-Unnecesary work. - Work not done properly at the first time. -Rework. -Stoppages. -Waste of materials. -Deterioration of materials. -Loss of labour. -Unnecessary momement of materials. -Excessive vigilance. -Extra supervision. -Delays in activities. -Extra processing. -Clarifications. -Abnormal wear and tear of equipment.

2.5 Green Construction

Green Construction is a concept that has spawned from the need and desire for more energy-efficient and environmentally friendly building practices, and it has taken over 60 years to become what it is today. Paolo Soleri, in the 1960s, introduced the concept of "Arcology," a combination of architecture and ecology (Piedmont-Palladino, 2006). This philosophy was used to create a healthy environment and comfortable social living spaces for communities. Nevertheless, it was in the 1990s that the green construction or green building movement began coming together. In 1992, the first United Nations Conference on Environment and Development (UNCED) took place in Rio de Janeiro, officially introducing the term "green building" (Hopkins, 2016). In the same year, the Environmental Protection Agency (EPA) and the Department of Energy launched the Energy Star program and joined hands to promote energy efficiency (EPA, 2016). The following year, the Green Revolution and the United States Green Building Council (USGBC) were founded to promote sustainability in designing, building, and operating buildings (EPA, 2016). Additionally, in 1998 USGBC partnered with the Federal Energy Management Program to launch the first version of the green building rating system, *Green Building Council's Leadership in Energy and Environmental Design*, better known as LEED, becoming the most widely used green building standard globally (USGBC, 2020).

Over the past decades, the concept of green construction has aroused to improve communities' living standards. Ahn & Pierce (2007) mentioned “The U.S Green Building Council defined green construction as a process to design the built environment while considering environmental responsiveness, resource efficiency, cultural and community sensitivity.(p.106)" Additionally, the U.S Environmental Protection Agency EPA (2016) mentioned, "green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient…" Subsequently, Shen, Zhao, and Ge (2020) stated, "The definition of green building is generally accepted as the planning, design, construction, and operation of buildings with the maximum conservation of resources (energy, land, water, and materials), environmental protection, pollution reduction, and providing people with healthy and comfortable indoor space. (p.1)" This practice focused on the standard building design concerns of durability, economy, comfort, and utility (Hopkins, 2016).

There are many definitions and terms to define green construction or green building. Robichaud and Anantatmula (2011), in *Greening Project Management Practices for Sustainable Construction*, established four green building characteristics:

1. Minimize or eliminate impacts on the environment, natural resources, and non-renewable energy sources to promote the sustainability of the built environment.

2. Enhance the health, wellbeing and productivity of occupants and whole communities.

3. Cultivate economic development and financial returns for developers and whole communities.

4. Apply life cycle approaches to community planning and development. (p.49)

These characteristics indicate that green construction decreases the built environment's social and environmental impacts while enhancing residents' quality of life within buildings. Laura B. Cole (2019) studied "the complex relationship between building elements and how these built features interact with the local communities and local environments, for example, human, air, water, plant, and animal life that are affected by the building (p.7)." This study focused on promoting green building education that connects complex topics towards a more conceptual understanding of green buildings into skills and actions.

MacNaughton et al. (2018), in *Energy savings, emission reductions, and health co-benefits of the green building movement,* analyzed the co-benefits to health through reductions in energy and contributing to the reductions in air pollution of six countries (the United States, China, India, Brazil, Germany, and Turkey) by using data from the Green Building Information Gateway (GBIG). This research demonstrated that green buildings had improved the health of millions of people and should be considered during the drafting of policy, the design of new buildings, and the operation of existing ones (MacNaughton et al., 2018). Dwaikat and Ali (2018) in *The economic benefits of a green building – Evidence from Malaysia* exhibit green building saved 71.1% of energy than the industry baseline, considering energy efficiency as a key operator for the green construction movement. Along similar lines, Ahnn and Pearce (2007) analyzed 30 companies in the construction industry in order to study contractor experiences, expectations, and perceptions associated with green building. The result showed that construction companies had believed that green construction was fundamental in implementing standards even though they still believed that the initial cost premium was very high compared to conventional construction.

Green building challenges the architecture, engineering and construction industries, changing how construction professionals create and build. As MacNaughton et al. (2018) say, "Buildings constructed today will be in use for decades to come and as such, decisions about their design and energy efficiency measures will substantially influence progress on mitigating climate change and reducing air pollution morbidity and mortality (p.1)." Hence, green construction's primary goal is to create a better environment, reducing the negative impact on human health, social and economic during the building process. For this reason, it is essential to understand green building as a part of the entire construction industry and as a standard to measure future variations in the industry over time (Ahnn and Pearce, 2007; Cole, 2019).

2.6 Modeling Equipment Operations.

Constructions equipment or heavy equipment is one of the significant inputs designed to execute construction tasks alongside labour resources and materials. It represents a significant capital investment for the construction industry; for example, it facilitates construction activities to be executed. Therefore, this equipment's objective is to make the construction process more cost-effective (Vorster, 2009).

Bayzid (2014) research focused on the study of equipment management systems. This study proposed a model/algorithm to predict maintenance costs for different road construction equipment. The main objective was to help the equipment manager to make decisions related to equipment maintenance costs. Furthermore, Sadha (2012) *Modeling Reclamation Earthwork Operations Using Special Purpose Simulation Tool* presented a unique simulation tool to model earthwork operations using Simphony.NET. The results showed a functional and technical simulation that could be used as a planning tool within the construction industry.

Chien, Gao, and Meegoda (2013) created a mathematical model to learn the required truck fleet size that considered impact of weather and traffic on truck speed. The fleet size is calculated using the total road surface area and the plowing area per plow. This model presents the deadheading (vehicle travelling without doing any maintenance work) from the depot to the working road section is neglected, and the vehicle routing in the road network is also not acknowledged. Nonetheless, the result demonstrated that fleet size had been reduced when increasing the plowing speed, and a larger truck fleet was needed as the precipitation amount increased.

Liu (2020) emphasized the importance of construction equipment management stating, "Construction equipment management is critical for the long-term success of construction companies. Managing equipment in a cost-efficient manner for a project or corporate operations is a key concern for construction companies." In this study, Liu proposed a mathematical model and a Social Network Analysis (SNA) to indicate current practices' limitations while introducing different approaches to evaluate equipment logistics performance, equipment acquisition, disposal, and financial sustainability. Following this idea, Waris, Liew, Khamid and Idrus (2014) focused on determining selection criteria based on sustainability's fundamental concept. While Ahn, Lee, Peña-Mora (2013) used low-cost accelerometers to measure construction equipment's operational efficiency and to monitor environmental performance.

2.7 Simulation Models.

Construction engineering combines physical components and professionals involved from the beginning to the completion of a project life cycle. Bokor et al (2019) mentioned “Construction simulation is a useful technique that replicates reality and provides valuable information on construction works. (p. 1859)”. The use of simulation tools in the construction industry focuses on techniques and procedures that address numerous challenges during the building period in an uncontrolled environment. As a result, AbouRizk, Haque and Ekyalimpa (2016) divided the life cycle of an engineering project into four phases which are essential in the completion of an engineering project:

1. Initiation referred to the starting point of any engineering project. In this phase, a strategic need for the project must be recognized by developing a project case, contract or work statement.

2. Planning referred to the creation of a project plan, workflow diagrams, project budget, and risk management, which will help identify possible constraints and understand each member of the team's role inside the project.

3. Execution, this phase is divided into three subphases: design, construction and testing. These phases may overlap; thus, engineering input and performance are continually measured to ensure the project is completed.

4. Operation referred to the project closure. It is the phase where the project owner can operate and use the facility.

The use of the life cycle helps to implement new approaches in the construction management process in order to solve problems related to the planning and execution of works, such as imprecise scheduling and inadequate allocation of roles and resources (Forcael et al., 2018). Therefore, construction engineers' role is essential to understand project life cycle phases, especially during the execution to identify construction errors in the early stages.

Rubio et al. (2005) stated, "The role of civil engineers... is of great importance, given that, in exercising their profession, whether in projecting, supervising, executing the work, or coordinating safety and health matters. (p.74)" Additionally, Murphy and Gardoni (2019) mentioned, "The responsibilities that are constitutive of being an engineer include striving to fulfill the standards of excellence set by technical codes; to improve the idealized models that engineers use to predict, for example, the behaviour of alternative designs; and to achieve the internal goods such as safety and sustainability as they are reflected in the design codes. (p. 1818)" Indeed, civil engineers assume heavy responsibilities and obligations in their profession, regardless of their roles within a project. Hence, delivering a good quality product calls for developing simulation models that are conducive to analyzing and communicating better different approaches.

2.7.1 What is Simulation?

Harries and Kahn in 1948 began the study and development of simulation techniques that were applied in different knowledge areas and disciplines (Aspray, 1990). Nevertheless, it is back to the 1920 and 1930 when the first machine and random tables were used in engineering simulation (Kelton, 1996). Geoffrey Gordon (1961) mentioned, "The need for Simulation has been generated by the ever-increasing complexity of systems that are being designed, while the speed and capacity of modern digital computers have provided the means by which to expand simulation efforts. (p. 87)" Certainly, simulation programs have evolved to solve problems in diverse fields.

Tang et al. (2004) defined Simulation as "the process of conducting experiments with a model of the system that is being studied or designed. It is a powerful technique for both analyzing and synthesizing engineering and other natural systems (p. 126)." Bokor et al. (2019) stated, "Simulation considers time changes and the dynamic nature of processes to model a system's operation. It can be applied, for instance, to model a construction operation to determine activity durations and resource usage more precisely, which can be used to make more realistic schedules and cost calculations. (p.1859)" Bennet and Ormerod (1984) in *Simulation Applied* *to Construction Projects,* described the advantages that simulation methods have on the construction industry, for example (p. 228):

- The validity of input assumptions provides an unbiased estimate of the project completion distribution.

- Provides an almost unlimited capacity to model construction operations and permits the construction manager to quickly evaluate many different combinations of equipment and methods under varying conditions of operation at a moderate cost.

- Simulation can give the manager an insight into which factors are important.

- Allows the user to experiment with different strategies without the risk of interrupting the real project and the incurred cost.

Along the same line, Sadowski and Grabau (2000) defined a simulation application's success as "one that delivers useful information at the appropriate time to support a meaningful decision. (p.26)" Indeed, the simulation method's purpose is to help professional engineers solve complex problems by developing better project plans while optimizing resource usage, minimizing costs or project duration, and improving overall construction project management (AbouRizk, 2010). Hence, the only limitation of simulation methods is time-consuming and verification of results with real-world data. This technique can sometimes provide reasonable solutions but not an optimal solution (Tang et al., 2004; Bennet & Ormerod, 1984).

2.7.2. Simulation Types.

Raoufi et al. (2016) defined that "Construction simulation is defined as the science of developing computer-based models of construction systems to understand their underlying behaviour. (p.01)" Application of simulation plays an essential role in the future of automated project planning and control. AbouRizk, Haque and Ekyalimpa (2016) suggested six types of simulation encountered in construction, such as (p.12):

- Dynamic Simulation Model: is a system that changes over time. It is used to model interventions before the cost-intensive design and development and implementation phases.

- Discrete Event Simulation Model: is a particular type of dynamic simulation model. This model is processed by advancing the time in discrete segments based on significant events in the model.

- Continuous Changes Model: is a type of dynamic model that is processed by incrementing time in uniform (equal) steps.

- Static Simulation Model: is a formulation of a component of the systems where the model remains the same regardless of the time's passage. Hence, the model does not change over time.

- Deterministic Simulation Model: is composed of elements that are all constant and do not change during the Simulation. These models are not useful for decision making but can be invaluable for model verification and debugging.

- Stochastic/Monte Carlo Simulation Model: refers to the model that incorporates random process during model execution. One example of a stochastic model is the Monte Carlos simulation in which the simulation objective includes probabilistic distribution to model their random nature.

Each simulation model has a unique characteristic that allows us to create a model and experiment to answer different questions. Hence, there is a simulation model called monolithic simulation that includes all model components confined into one. AbouRizk, Haque and Ekyalimpa (2016) defined, "monolithic simulation is one in which all model components are localized into one, such that they all execute and terminate at the same time, and are normally run on one computer. (p.22)" Indeed, this simulation creates a flexible environment that improves both numerical stability and efficiency.

2.7.3 Simulation Applications.

Simulation software provides a dynamic environment for analyzing computer models while solving real-world problems safely and efficiently. Fujimoto (2000) declared "simulation software as a system that emulates another system using computers (p. 27)" There are a diverse number of simulation software systems that are used for academic and commercial purposes. These simulation software systems have the same principle. For instance, SIMPHONY, as simulation software, offers unique capabilities. As AbouRizk, Haque and Ekyalimpa (2016) mentioned, "Simphony was developed to allow simulation tools to build on the fly… also allow the development of systems, called templates, which use icons that closely represent elements from real-world problems to build simulations models (p.24)"

There have been many studies where simulation has been applied. For example, Newstead (2015), in *The Application of Front End Planning and Special Purpose Simulation Templates to Drainage Tunnel Construction,* used the simulation model SIMPHONY to create and analyze simulation temples to confirm alternate construction methods, scheduling and budget deadlines in tunnel constructions. Hammad et al. (2002), in *Simulation Model for Manufactured Housing Processes,* discussed the demand for manufactured houses by developing a simulation model in Arena to analyze the production process. Lee and Ibbs (2005) used the Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) software to predict and analyze different scenarios at each pavement rehabilitation project stage. They mentioned the simulation software "provides a construction schedule baseline for the integration of design, construction, and traffic, all of which are essential for the selection of the most economical pavement rehabilitation strategies." Murphy and Perera (2001), in the article *The Definition and Potential Role of Simulation Within an Aerospace Company,* used simulation software in the airframes' manufacturing industry. This study demonstrated the merge of theoretical data and simulation programs in order to bring essential results in the manufacturing industry.

Simulation is a powerful decision-support tool for workers that observe projects' conditions and performance. Moreover, simulations provide greater flexibility towards tasks like generating random numbers from a probability distribution, advancing simulation time, determining the next event, collecting and analyzing data, reporting the results and adding or deleting records. These characteristics are instrumental in developing a better alternative by reducing risk, budget development, claims, dispute resolution, planning and control.

2.8 Earthwork Equipment in the Construction Industry.

Equipment management in the construction industry plays a pivotal role in the economic and environmental goals. Especially in the field of civil works, proper management of scrapers and haulers represent an opportunity to reduce cost, deliver projects on time and mitigate adverse impacts to the environment that are related to the project. Thus, the impact of equipment life that considers environmental impacts is essential for the sustainability of a project.

The acquisition cost of earthmoving construction equipment represents a significant investment for construction companies since most of this equipment cost at least $100,000. As a result, equipment owners need to ensure their property is utilized, maintained, and managed efficiently.

Although earthwork equipment can perform varied tasks in different locations and can be easily stored on and off the job-site, it does not represent a fixed asset (Peurifoy et al.,2018). The value of the equipment is consumed in the production of work. Hence, the owner's goal is to acquire as much work possible from the equipment before it becomes obsolete. Since all excavators have a limited number of mass handling it can do, and haulers have a finite number of trips it can perform, these machines are involved in frequent transactions of purchasing, renting or leasing during their equipment life. Equipment life can be defined in three different ways, as shown in Figure 2-2.

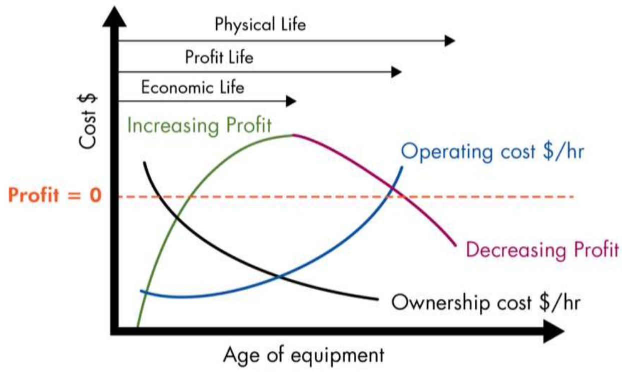

Figure 2-2. Equipment Life (University of Toronto, 2017)

- Physical life: The total time that the equipment can be operated. This period is greatly affected by the repairs and maintenance required by a piece of equipment during its lifespan. For example, an excavator or hauling truck that is not given adequate maintenance or repairs during its lifespan will usually deteriorate faster than a machine with proper maintenance (Gransberg et al. 2006).

- Profit life: Refers to the time where equipment is generating profits. This period takes place before significant components of the equipment begin to wear out, causing the equipment to work with loss, due to high maintenance costs. For an owner, this is the most crucial time in the age of equipment, as it represents the opportunity to maximize profitability and efficiencies (Gransberg et al. 2006)

- Economic life: Refers to the time where decreasing ownership costs and increasing operating costs are equivalent. As operating costs exceed ownership costs, a piece of equipment costs more to operate than to own. Thus, an owner will tend to replace a piece of equipment before the end of the economic life is reached (Gransberg et al. 2006).

2.9 Financial Assessment of Emissions.

A subject that has received extensive research over the last years is the assessment of the economic impacts that emissions have on road-related projects. Individuals and public organizations frequently express their concern over the negative impacts that new transportation projects have on communities. In order to study the environmental costs associated with all stages of road development (i.e., design, construction, implementation, operation, maintenance and salvage cost), researchers established a process called Life Cycle Assessment (LCA) (Samieadel & Golroo, 2017). It is important to note that although several studies have proposed approximate fees for production of specific emissions in various industrial processes, there has not been a formerly established fee for the production of emissions in the construction industry at large and earthwork operations in particular.

The component of LCA that is responsible for assessing the economic impacts of an asset is called the life cycle cost analysis (LCCA). LCCA measures the monetary values of the processes associated with a product or system (Stanford University, 2005). The performance of LCCA is dependent on the development of several modules that study each aspect of road development. The most common LCCA modules used for earthwork operations include Material Module, Construction Module, Congestion Module, Usage Module, and End of Life Module (EOL). Each module takes into consideration the following (Samieadel & Golroo, 2017):

- Material Module: Considers every procedure in material production.
- Construction Module: Considers every activity related to the construction process.
- Congestion Module: Considers every activity related to the maintenance and rehabilitation of earthwork operations.
- Usage Module: Considers all the activities that take place after the road has been formerly built.
- EOL Module: Considers the demolition and disposal of the road at its end of life.

The use of LCCA has been used in many studies to establish the cost of emissions associated with a specific process. Zapata and Gambatese (2005) used LCCA to compare the environmental costs associated between asphalt concrete pavement and continuously reinforced concrete pavement. Cass and Mukherjee (2011) used LCCA to estimate greenhouse gas emissions and determine the environmental costs associated with highway construction and rehabilitation. Yu (2013) developed an environmental assessment of hot mix asphalt, plain concrete pavement and reinforced concrete pavement via LCCA (Yu, 2013). While, Samiadel and Golroo (2017) developed an index to measure sustainability of road-related projects through LCCA.

2.10 Lewis' Fuel Use and Emission Rate Estimates.

In 2009, Michael Lewis published a dissertation on estimating fuel use and emission rates of construction equipment. The purpose of Lewis' work was to provide the field of construction engineering with a tool that quantifies the environmental impacts that construction equipment and processes may have on a project. To accomplish so, Lewis collected extensive field data from non-road diesel equipment and created a methodology to determine fuel use and emissions rates as a function of mechanical and activity attributes. This section gives an overview of Lewis' dissertation.

2.10.1 Introduction.

A major limitation that the construction industry has attempted to overcome is the assessment of environmental impacts created in projects. One aspect of this limitation is the ability to determine how the machinery selected by construction managers causes much environmental damage. Early studies attempted to quantify the impact of equipment. For example, Ahn et al. (2013) provided a point of reference to analyze the energy consumption and air emissions resulting from buildings and construction sectors in the U.S and Canada, demonstrating the effort to achieve environmentally sustainable construction processes. On the other hand, Abolhasani et al., (2012) in *Real World in use Activity, Fuel Use, and Emissions for Nonroad Construction Vehicles: A Case Study for Excavators,* exhibited the relevance of "accounting for intercycle variability in real-world in-use emissions to develop more accurate emission inventories. (p.1033)" The article shows, there is a vital need to study real-world, on-board data to understand the relationship between construction equipment duty cycles concerning energy use and emissions. Most of these early studies developed methodologies that quantify emissions and fuel use based on steady-states engines. Because of this, these methodologies do not consider in-use equipment activity and provide results that fail to reflect the actual amount of pollution created in the field.

As Lewis realized there was a need to determine fuel use and emission rates of equipment based on in-use measurement methods, he decided to quantify the actual construction activity and its influence on fuel use and emissions via field data collection. Nevertheless, Lewis understood that constantly measuring fuel use and emission of pollutants was impractical. Thus, a data-based field methodology that could be used in the same manner as other standard construction estimates was the ultimate goal.

There are many benefits in developing a data-based field methodology that could be used in the same manner as other common estimate tools. For example, all construction projects have an environmental footprint regardless of size and type and being able to accurately estimate fuel use and emission may allow managers to find better financial alternatives to complete their projects. Additionally, environmentalists and policymakers would be interested in applying such a tool as it will benefit the quality of air.

Overall, Lewis conducted the following tasks to develop his methodology for estimating fuel use and emission rates (Lewis, 2009):

- Collected field data from two studies related to fuel use and emissions of 35 items of diesel construction equipment.

- Identified and assessed engine parameters that affect fuel use and emission rates.

- Developed an engine-based model analysis.

- Processed the collected field data by using statistically valid models.

- Established mathematical equation to determine fuel use and emission rates as functions of engine and activity modes.

2.10.2 Field Measurements.

The initial obstacle to conducting an appropriate field measurement is an adequate characterization of vehicle emission. During the use of diesel vehicles, the primary pollutants are NOx, HC, CO, and PM. These pollutants have several factors that influence the quantity of their productions, such as engine activity and task durations. For example, Figure 2-3 illustrates the typical work of a loader. During a work cycle, a loader burns diesel to travel, scoop and dump dirt, and relocate. While this work cycle is being performed, emissions are constantly produced.

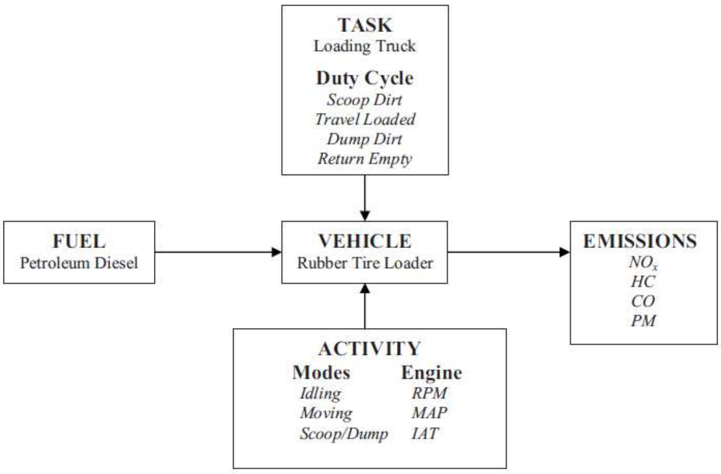

Figure 2-3. Production of Construction Vehicles. Reprinted from *Field Procedures for Real-World Measurements of Emission from Diesel Construction Vehicle* (p.217) by Rasdorf, W et al., 2010, ASCE by Journal of Infrastructure Systems

In his data collection, Lewis (2009) applied a method that consists of second-by-second engine activity measurements and emission through a portable emissions monitoring system (PEMS). A PEMS is a small and light device mounted on motor equipment and connected to an engine to gather air pollutant emission data. To create the connection between PEMS and an engine, sensors and a sample probe are inserted into the equipment's tailpipe while the vehicle performs work. As the probe collects information on pollutants, the sensors monitor the engine performance by tracking Revolutions Per Minute (RPM), values for Manifold Absolute Pressure (MAP), and Intake Air Temperature (IAT) (Lewis, 2009).

Lewis (2009) also used PEM to measure specific vehicle activities and engine parameters. These vehicle activities are known as ‘activity modes’ and include tasks such as idling, moving, loading, compacting, and more. The duration of each activity mode is measured by seconds, while specific engine parameters are monitored. These engine parameters are known as ‘engine modes’ and include revolutions per minute (rpm), intake air temperature (IAT), and manifold absolute pressure (MAP). Thus, Lewis (2009) combined the information from these activity modes and engine parameters to establish a relationship to quantify diesel equipment emissions.

For his study, Lewis (2009) selected construction equipment that produced the highest quantities of pollutants based on analyses using the EPA NONROAD model (EPA, 2008). Summary of equipment types, model and equipment attributes can be seen in Tables 1 - 4

Table 2-2. Summary of Equipment Types.

Equipment Type	Equipment Tested
Backhoe	8
Bulldozer	6
Excavator	3
Motor Grader	6
Off-Road Truck	3
Track Loader	3
Wheel Loader	5

Note. Reprint from *Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

Table 2-3. Summary of Horsepower and Displacement Ranges for Each Equipment Type.

		Horsepower (HP)		Displacement (liters)	
Equipment Type	Number Tested	Minimum	Maximum	Minimum	Maximum
Backhoe	8	88	99	3.9	4.5
Bulldozer	6	89	285	3.9	14.2
Excavator	3	93	254	3.9	8.3
Motor Grader	6	160	198	7.1	8.3
Off-Road Truck	3	285	306	9.6	10.3
Track Loader	3	70	149	4.5	7.2
Wheel Loader	5	88	133	4.0	6.0

Note. Reprint from *Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

Table 2-4. Summary of Engine Model Year for each Equipment Type.

		Model Year	
Equipment Type	Number Tested	Minimum	Maximum
Backhoe	8	1997	2004
Bulldozer	6	1988	2005
Excavator	3	1998	2003
Motor Grader	6	1990	2007
Off-Road Truck	3	1998	2005
Track Loader	3	1997	2006
Wheel Loader	5	2002	2006

Note. Reprint from *Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

Table 2-5. Summary of Engine Model Year for each Equipment Type.

		Engine Tier Classification			
Equipment Type	Number Tested	Tier 0	Tier 1	Tier 2	Tier 3
Backhoe	8	1	4	3	0
Bulldozer	6	2	3	1	0
Excavator	3	0	2	1	0
Motor Grader	6	2	2	1	1
Off-Road Truck	3	0	2	1	0
Track Loader	3	1	0	2	0
Wheel Loader	5	0	1	2	0

Note. Reprint from *Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

As per the EPA NONROAD model (EPA 2008), these vehicles are estimated to contribute over 70% of all NOx, CO, and PM from construction vehicles in the United States. Following the identification of vehicle emissions that need to be quantified, the next obstacle is figuring out what can be determined with emission quantification. If time and emissions are measured simultaneously, they can be directly related to mass-produced per time (g/s). Similarly, emissions can be directly measured in fuel consumption based on a carbon balance (g/gal). Correspondingly, it is also possible to relate emissions to activity modes and engine parameters (Lewis, 2009). Therefore, having various methods to assess vehicle emissions allow construction managers to develop strategies for emission reduction.

Lewis (2009) focused his emissions measurements on activity modes, and engine parameters as the type of task and cycle characteristics have a major impact on the engine load of a vehicle.

For example, a loading truck travelling with full cargo will impose a higher load on its engine than travelling with empty cargo. Similarly, as higher loads are imposed on its engine, higher quantities of emissions are produced.

The primary source for data collection obtained by Lewis (2009) was from a number of construction activities performed on the campus of North Carolina State University in Raleigh, NC. During his data collection, construction vehicles were equipped with PEMS for gathering field use and emission data, a laptop to record activity modes, a global positioning system (GPS) for documentation location, and a video camera to obtain visual data related to the equipment and the process of the project.

When a piece of equipment began operation, the PEMS and the laptop collected fuel use and emission data. The PEMS frequently collected fuel use and emissions data, engine parameter and location data, while the laptop collected data equipment activity and mode data. Each activity mode was classified in the laptop, and each time a piece of equipment began an activity mode, like the ones shown in Figure 2-3, the laptop would record the duration of each activity mode.

Additional information that was gathered during Lewis' study was the equipment data. This data included information on the Identification, chassis and engine. The Identification included the manufacturer's Vehicle Identification Number (VIN). Chassis information included manufacturer, model number, make a year, and gross vehicle weight (GVW). Engine information included manufacturer, model number, make year, aspiration, displacements, horsepower, and number of cylinders. This additional information was gathered to compare fuel and emissions data based on the equipment's engine and the equipment type.

The collection of data also encountered a series of obstacles. One of them was unsuitable weather for the use of data collection equipment. The PEMS was an electro-mechanical device that was not designed to be used in construction sites. Thus collection of data could not occur during a rain or snow event. Therefore, data were collected when the temperature was between 2°C and 31°C.

In order to certify the quality of the data, a minimum of three hours of second-by-second data were collected from each piece of equipment that was tested. The field data was evaluated to determine whether any errors existed in the process of collection. If any errors were found, they were corrected when possible, and in the instances where no corrections were possible, the invalid data was removed. The typical data errors found during the collection were unusual IAT, MAP, RPM values, and negative emission values. Frey et al., (2008) in technical report *Real-World Duty Cycles and Utilization for Construction Equipment in North Carolina* exposed a general overview of data quality assurance adopted by Lewis. In this technical paper, the quality field data collection from vehicle emissions mostly depends on the synchronization between engine data and concentration data, as shown in Figure 2-4. To certify that a proper synchronization has been established during field measurements, data quality checks associated with sensor arrays, gas analyzers and air leakage need to be performed.

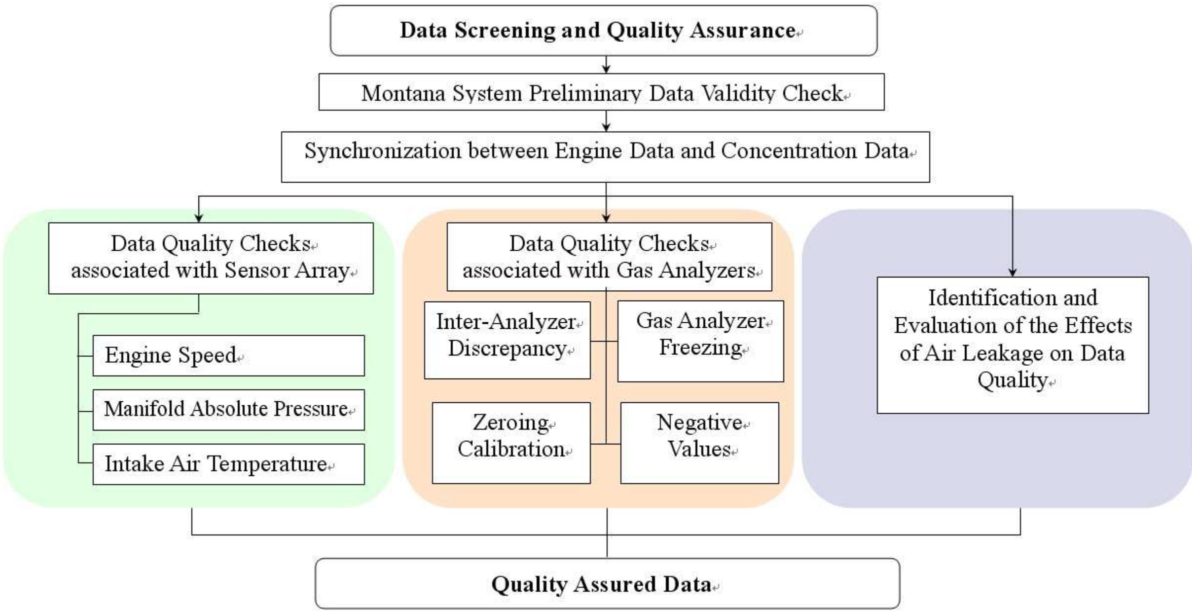

Figure 2-4. Overview of Data Quality Assurance Procedures. Reprinted from *Real-World Duty Cycles and Utilization for Construction Equipment in North Carolina*. (p.21) by Frey et al.,2008, North Carolina State University.

By the end of his data collection, Lewis had tested 49 pieces of construction equipment. These include eight backhoes, six motor grader, three excavator, six motor grader and three off-road trucks. Table 2-6 shows a summary of the data collected by Lewis for each type of equipment.

Table 2-6. Summary of Data Collection Results for Each Piece of Equipment.

Equipment Item	Data Collection Results: Field (seconds)	Quality Assured (seconds)	Invalid (%)
Backhoe 1	9,335	8,898	5
Backhoe 2	20,415	13,407	34
Backhoe 3	10390	9854	5
Backhoe 4	9,226	8,297	10
Backhoe 5	11,567	10,551	9
Backhoe 6	18,237	16,407	10
Backhoe 7	8,647	8,354	3
Backhoe 8	9,105	8,555	6
Bulldozer 1	29,180	28,690	2
Bulldozer 2	41,931	40,691	3
Bulldozer 3	18,412	18,147	1
Bulldozer 4	13,533	12,698	6
Bulldozer 5	11,352	11,309	0
Bulldozer 6	10,542	5,161	51
Excavator 1	54,848	53,487	2
Excavator 2	20,044	19,697	2
Excavator 3	20,644	18,326	11
Motor Grader 1	16,348	15,727	4
Motor Grader 2	12,205	11,704	4
Motor Grader 3	7,860	7,663	3
Motor Grader 4	11,500	10,040	13
Motor Grader 5	10,602	9,789	8
Motor Grader 6	9,262	8,687	6
Off-Road Truck 1	27,100	21,746	20
Off-Road Truck 2	5,574	5,084	9
Off-Road Truck 3	13,588	8,464	38
Track Loader 1	7,198	5,516	23
Track Loader 2	14,184	10,502	26
Track Loader 3	13,205	9,921	25
Wheel Loader 1	17,908	17,785	1
Wheel Loader 2	20,217	19,064	6
Wheel Loader 3	12,974	12,876	1
Wheel Loader 4	10,950	10,667	3
Wheel Loader 5	10,774	10,434	3
	550,758	**499,859**	**9**

Note. Reprint from *Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

Once the data was collected, Lewis took the following steps to estimate fuel use and emission rates of construction equipment (Lewis, 2009):

1. Identify and quantify equipment attributes that affect fuel use and emission rates.

2. Perform an engine modal analysis for each type of equipment.

3. Develop engine modal fuel use and emission rates for each engine mode though statistical analysis.

4. Determine time spent in each engine mode and fraction of fuel used in each engine mode through the study of representative duty cycles.

5. Establish the weighted-average fuel use rate cycle by multiplying the modal fuel use rate by the fraction of time spent in each engine mode.

6. Establish the weighted average emission rate for each pollutant by multiplying the modal emission rate for each engine mode by the fraction of fuel used in each engine mode.

7. Convert the mass per fuel used weighted-average emission rate to a mass per time weather average emission rate.

2.10.3 Equipment Attributes Affecting Fuel Use and Emissions.

Following data collection, Lewis (2009) considered the following attributes of equipment to formalize a categorization method:

1. Equipment Type: As there are many types of equipment that can perform several construction tasks and others that can only perform specific duties, there is a great variety of performance. Lewis performed this study using multi-purpose equipment in earth-moving operations. By doing so, the results obtained are mainly applicable to earthwork equipment.

2. Engine Size: Since the size of the equipment's engine affects its fuel and emission rates. It is essential to consider the engine size. As a result, the engine's rated horsepower needs to be collected.

3. Engine Age: Over time, engines have become less efficient, mainly when used extensively. The efficiency of a used engine depends on whether it was used and maintained correctly. Because of this, the engine's age plays a role in fuel use and emission rates.

4. Engine Load: As individual construction activities impose different loads on equipment's engine, it is inappropriate to assume that an engine will continuously work at a full load. To consider this fact, Lewis determined the engine load by measuring the Manifold Absolute Pressure (MAP) of the engine, as MAP has been found to have a high correlation with fuel use and emission rates (Frey et al., 2007).

5. Engine Tier: Refers to a classification standard established by EPA in 1994 for all new non-road diesel engines (Lewis, 2009). The classification standard is based on both engine age and size and can be seen in Table 2-7.

Table 2-7. EPA Classification Standard.

Engine Horsepower (HP)	Model Years	Regulation	Emission Standards (g/hp-hr)				
			HC[1]	NMHC + NO_x	CO	NO_x	PM
50 ≤ HP < 75	1998 – 2003	Tier 1	NS	NS	NS	6.9	NS
	2004 – 2007	Tier 2	NS	5.6	3.7	NS	0.30
	2008 – 2012	Tier 3	NS	3.5	3.7	NS	0.22
	2008 – 2012	Tier 4 Transitional[2]	NS	3.5	3.7	NS	0.22
	2013 +	Tier 4 Final[2]	NS	3.5	3.7	NS	0.02
75 ≤ HP < 100	1998 – 2003	Tier 1	NS	NS	NS	6.9	NS
	2004 – 2007	Tier 2	NS	5.6	3.7	NS	0.30
	2008 – 2011	Tier 3	NS	3.5	3.7	NS	0.30
	2012 – 2013	Tier 4 Transitional[3]	0.14 (50%)	NS	3.7	0.30 (50%)	0.01
	2014 +	Tier 4 Final	0.14	NS	3.7	0.30	0.01
100 ≤ HP < 175	1997 – 2002	Tier 1	NS	NS	NS	6.9	NS
	2003 – 2006	Tier 2	NS	4.9	3.7	NS	0.22
	2007 – 2011	Tier 3	NS	3.0	3.7	NS	0.22
	2012 – 2013	Tier 4 Transitional[3]	0.14 (50%)	NS	3.7	0.30 (50%)	0.01
	2014 +	Tier 4 Final	0.14	NS	3.7	0.30	0.01
175 ≤ HP < 300	1996 – 2002	Tier 1	1.0	NS	8.5	6.9	0.40
	2003 – 2005	Tier 2	NS	4.9	2.6	NS	0.15
	2006 – 2010	Tier 3	NS	3.0	2.6	NS	0.15
	2011 – 2013	Tier 4 Transitional[3]	0.14 (50%)	NS	2.6	0.30 (50%)	0.01
	2014 +	Tier 4 Final	0.14	NS	2.6	0.30	0.01
300 ≤ HP < 600	1996 – 2000	Tier 1	1.0	NS	8.5	6.9	0.40
	2001 – 2005	Tier 2	NS	4.8	2.6	NS	0.15
	2006 – 2010	Tier 3	NS	3.0	2.6	NS	0.15
	2011 – 2013	Tier 4 Transitional[3]	0.14 (50%)	NS	2.6	0.30 (50%)	0.01
	2014 +	Tier 4 Final	0.14	NS	2.6	0.30	0.01
600 ≤ HP < 750	1996 – 2001	Tier 1	1.0	NS	8.5	6.9	0.40
	2002 – 2005	Tier 2	NS	4.8	2.6	NS	0.15
	2006 – 2010	Tier 3	NS	3.0	2.6	NS	0.15
	2011 – 2013	Tier 4 Transitional[3]	0.14 (50%)	NS	2.6	0.30 (50%)	0.01
	2014 +	Tier 4 Final	0.14	NS	2.6	0.30	0.01
750 ≤ HP (except generators)	2000 – 2005	Tier 1	1.0	NS	8.5	6.9	0.40
	2006 – 2010	Tier 2	NS	4.8	2.6	NS	0.15
	2011 – 2014	Tier 4 Transitional	0.30	NS	2.6	2.6	0.075
	2015 +	Tier 4 Final	0.14	NS	2.6	2.6	0.03

NS = No Standard

[1] Tier 4 standards are in the form of non-methane hydrocarbons (NMHC).

[2] The Tier 3 NO_x standard of 3.5 g/hp-hr was implemented beginning in 2008. The Tier 4 Transitional standard also begins in 2008, leaving the Tier 3 NO_x standard unchanged but adding a 0.22 g/hp-hr PM standard.

[3] Percentages are model year sales fractions required to comply with the indicated NO_x and NMHC standards for model years where less than 100% is required.

Note. Reprint from *Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P,. p. 46, 2009 by University of North Carolina.

2.10.4 Modal Analysis

Once a categorization method had been formalized, Lewis conducted two modal analyses to determine the impact of equipment and engine activity on fuel use and emission rate. One of these analyses is referred to as the activity modal analysis while the other is called the engine modal analysis.

The activity modal analysis categorizes data based on what the piece of equipment is doing, such as idling or working. This categorization was performed by the PEMS and the laptop that recorded second-by-second data into activity mode categories and then calculating the average fuel use and emission rates for each activity mode. After the calculation, the measuring devices would express the average use rate on a mass per time basis in terms of grams of fuel consumed per second (g/s). The results obtained in his study through the modal activity analysis for a type of equipment can be seen in the figure below. Table 2-4 shows that activity modes are not common among all the pieces of equipment evaluated by Lewis (Lewis, 2009). Table 2-4 displays the distinct activity modes assigned to each piece of equipment.

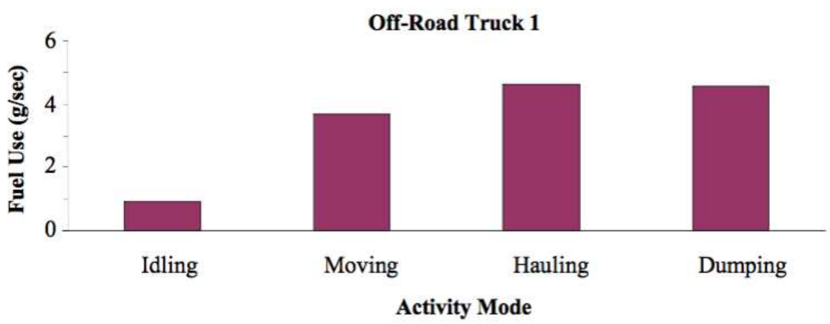

Figure 2-5. Sample Results from Activity Modal Analysis on an Off-Road Truck. *Reprint from Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

Table 2-8. Activity Classification for Construction Equipment (Lewis, 2009).

Equipment	Activity Mode
Backhoe	Idling
	Scoop/Dump Front Bucket
	Scoop/Dump Rear Bucket
Bulldozer	Idling
	Forward
	Reverse
	Blade
Excavator	Idling
	Moving
	Scoop/Dump
	Cycle
Motor Grader	Idling
	Moving
	Blade
Hauling Truck	Idling
	Moving
	Hauling
	Dumping
Loader	Idling
	Moving
	Scoop/Dump

Note. *Reprint from Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

By categorizing the second-by-second data into activity mode categories and then calculating the average fuel use and emission rates for each activity mode, the average fuel use rate is expressed on a mass per time basis, i.e., Grams of fuel consumed per second (g/s). The rate of emissions is expressed on a mass per time basis (g/s) or a mass per fuel basis in terms of grams per gallon of fuel used (g/gal). Hence, it is because emission rates are sensitive to idling and non-idling modes with respect to fuel consumption. However, time-based emission rates are more sensitive to engine loads imposed by working modes than fuel-based emissions rates. (Lewis, 2009)

The engine modal analysis categorizes data based on a range of engine loads imposed on the engine. Lewis normalized the values of MAP to use as an indicator of engine performance. The recorded MAP values for a piece of equipment were normalized through equation 1:

$$MAP_{nor} = \frac{MAP - MAP_{min}}{MAP_{max} - MAP_{min}} \quad (1)$$

where,

MAP_{nor} = Normalized MAP for a measure MAP for a specific item of equipment.

MAP_{max} = Maximum MAP for a specific item of equipment.

MAP_{min} = Minimum MAP for a specific item of equipment.

MAP = Measured MAP for a specific item of equipment.

The normalized values of MAP range from 0 to 1, creating 10 engine modes. These modes were defined as 0.0 to 0 .1, 0.1 to 0.2, 0.2 to 0.3, 0.3 to 0.4, 0.4 to 0.5, 0.5 to 0.6, 0.6 to 0.7, 0.7 to 0.8, 0.8 to 0.9, and 0.9 to 1.0. For example, engine mode 1 refers to normalized values between 0.0 and 0.1.

Through the engine modal analysis, fuel use and emission rates are quantified by arranging the second-by-second data into engine mode categories and then calculating the average fuel use and emission rates for each of them. The engine modal analysis produced the fuel use rates in terms of grams of fuel consumed per second (g/s). The results obtained by Lewis through the activity modal analysis for a type of equipment can be seen in Figure 2-6.

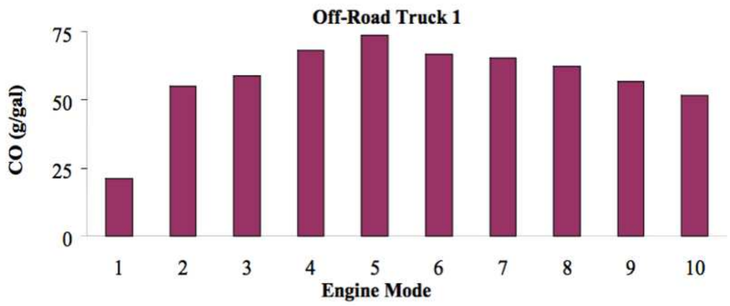

Figure 2-6. Sample Results from Engine Modal Analysis of Hauling Truck. *Reprint from Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

By categorizing the data into engine mode categories and then calculating the average fuel use and emission rates for each engine mode, the average fuel use rate is established in terms of grams of fuel consumed per second (g/s). Although the convention unit to measure emission in a mass unit (ton), the rate of emissions is expressed as a mass per time basis (g/s) or a mass per fuel in terms of grams per gallon of fuel used (g/gal). This is because emission rates are highly sensitive to each engine mode and fuel-based emission rates are more robust for equipment emission estimating purposes (Lewis, 2009).

By evaluating the data classification from the engine modal analysis and the activity modal analysis, Lewis determined that although emission states are sensitive to idling and working modes, the load imposed on engines has a more significant influence on emissions production. Therefore, estimating fuel use and emission rates based on engine modes' data classification will have a more accurate result.

2.10.5 Fuel Use and Emission Rates Through Engine Modes

Lewis determined the fuel and emission rate of each pollutant for each engine mode by either using the average fuel use and emission rate for each mode or by developing a mathematical relation for each engine model based on multiple linear regressions (MLR).

Based on 34 evaluated pieces of construction equipment and the data classification by the engine modal analysis, Lewis determined the average fuel use and emission rate of each pollutant for each engine mode. Table 2-5 shows the results obtained for each engine mode. Each average was calculated with outliers and without outliers. And the percentage difference between the two averages is also presented. The percentage difference shows the impact that outliers have on the production of pollutants.

Table 2-9. Average Fuel Use and Emission Rates per Engine Mode (Lewis, 2009).

		Engine Mode									
		1	2	3	4	5	6	7	8	9	10
Fuel Use (g/s)	With Outliers	0.63	1.39	1.99	2.54	2.98	3.45	3.96	4.49	5.08	5.63
	Without Outliers	0.63	1.31	1.66	2.11	2.65	2.65	3.74	4.23	4.78	5.31
	% Difference	*0*	*5*	*17*	*17*	*11*	*23*	*6*	*6*	*6*	*6*
NO_x (g/gal)	With Outliers	156	137	125	118	114	113	109	111	111	113
	Without Outliers	156	129	121	113	109	109	103	105	104	106
	% Difference	*0*	*6*	*3*	*4*	*4*	*3*	*6*	*6*	*6*	*6*
HC (g/gal)	With Outliers	27	24	20	15	13	12	12	11	11	9
	Without Outliers	22	14	12	13	11	10	10	9	9	8
	% Difference	*17*	*42*	*37*	*18*	*12*	*12*	*18*	*15*	*18*	*13*
CO (g/gal)	With Outliers	53	54	48	40	37	35	32	31	30	28
	Without Outliers	45	46	33	30	28	27	23	21	20	19
	% Difference	*14*	*14*	*31*	*25*	*24*	*25*	*29*	*34*	*34*	*33*
CO_2 (kg/gal)	With Outliers	9.9	9.9	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
	Without Outliers	9.9	9.9	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
	% Difference	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
PM (g/gal)	With Outliers	0.99	1.03	1.00	0.96	0.99	1.07	1.04	1.11	1.02	1.09
	Without Outliers	0.82	0.97	0.94	0.92	0.96	1.02	0.96	1.00	0.90	0.90
	% Difference	*18*	*6*	*6*	*3*	*3*	*5*	*8*	*10*	*13*	*17*

Note. *Reprint from Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

The development of mathematical equations to relate equipment's attributes and its fuel use and emission rates are based on the data collected from 34 construction vehicles and MLR. These attributes include horsepower, displacement, model year, equipment type, and engine tier. The predictive models were developed for engine modes 1 - 10, and similarly to the average fuel use and emission rates, some models included data with outliers and other excluded outliers. For emission rate estimates, Lewis developed models for the emission rates of NO_x, HC, CO and PM for engine mode 1 - 10. Table 2-6 shows the developed models that estimate the fuel use rate for each engine mode.

Table 2-10. Fuel Use Rate Models for Each Engine Mode (Lewis, 2009).

Mode	Model	S	R^2	R^2-adj
1	fuel[g/s] = 0.6 [1]	NA	NA	NA
2	fuel[g/s] = - 0.364 + 0.0112 HP + 0.565 TIER_0	0.5	76	75
3	fuel[g/s] = - 0.620 + 0.0166 HP + 0.876 TIER_0	0.7	77	75
4	fuel[g/s] = - 0.882 + 0.0216 HP + 1.29 TIER_0	0.9	76	74
5	fuel[g/s] = - 0.908 + 0.0244 HP + 1.56 TIER_0	1.0	77	76
6	fuel[g/s] = - 1.05 + 0.0283 HP + 1.81 TIER_0	1.1	77	76
7	fuel[g/s] = - 1.30 + 0.0332 HP + 2.03 TIER_0	1.3	78	76
8	fuel[g/s] = - 1.39 + 0.0368 HP + 2.47 TIER_0	1.4	78	77
9	fuel[g/s] = - 1.68 + 0.0422 HP + 2.93 TIER_0	1.6	80	78
10	fuel[g/s] = - 1.66 + 0.0458 HP + 2.93 TIER_0	1.6	81	80

Note. *Reprint from Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

The application of the fuel use rate models for each engine mode shown in Table 2-6, and the average emission rate per engine mode shown in Table 2-5, allowed Lewis to determine the weighted average fuel use rate (gal/hr) and the weighted average emission rate (g/hr). To get these values, Lewis uses Equation 2 and Equation 3:

$$Fuel_{wt.avg} = \sum_{i=1}^{n} F_{time(i)} * A_i * CF \tag{2}$$

where,

$Fuel_{wt.avg}$ = Weighted-average fuel use rate (gal/hr).

$F_{time(i)}$ = Fraction of time spent in engine mode i.

A_i = Estimated fuel use rate (g/s) for mode i.

CF = Conversion factor (1.132) to convert g/s to gal/hr

$$E_{J.wt.avg} = Fuel_{wt.avg} * \sum_{i=1}^{n} F_{fuel(i)} * B_{ij} \tag{3}$$

where,

$E_{J.wt.avg}$ = Weighted-average emission rate (g/hr).

$Fuel_{wt.avg}$ = Weighted-average fuel use rate (gal/hr) for n engine modes

$F_{fuel(i)}$ = Fraction of fuel used in engine mode i.

B_{ij} = Emission rate (g/gal) for pollutant j and engine mode i

2.10.6 Limitation of Lewis' Study

Lewis' methodology is successful in establishing a relationship between energy consumption and emission from construction equipment based on field data and mechanical attributes. Nevertheless, his methodology is limited by obstacles associated with data collection. Gathering second-by-second information from running equipment in active sites represents an expensive and time-consuming undertaking. Additionally, several equipment types and models are used in the day-to-day operations of a typical construction project; therefore, it is impractical to measure fuel use and emission from each of them. As such, the developed fuel use rates and emission equations are based on limited data.

The methodology to collect data also contains limitations. One of these limitations is the inability for the PEMS to operate during a rain or snow event as it's a device designed for use in moderate weather. Extensive vibration, dust and mud could cause the PEMS to malfunction.

Another limitation in Lewi's study is that his field data collection and evaluation did not explicitly factor in the impact that site conditions (like haul road grading and rolling factors) had on earthwork equipment performance.

Despite the limited data collected by Lewis and limitations created by the PEMS, the classification of engine modes and the average emission measurements under each mode provide valuable input to establish a relationship between energy consumption and the production of pollutants.

2.10.7 Similar work to Lewis' Study

As environmental assessment inclusion into construction processes has been a focal point of research in the recent years, similar methodologies had been formalized to estimate emission from nor-road diesel equipment. One of these methodologies is the use of the NONROAD Model. The Environmental Protection Agency's NONROAD model estimates NONROAD equipment emission based on fleet average emission rates. The study leading up to the development of this model included over 260 specific equipment types classified by equipment time and horsepower. The NONROAD model estimates emissions in tons per year based on an average engine load factor, available horsepower, equipment activity (hours per year), and emission factors based on deterioration or new standards (EPA, 2005). A key limitation associated with the NONROAD Model is that the estimated emissions were based on an average load factor that didn't account for how the equipment was being operated and site conditions.

The California Air Resources Board (CARB) also developed a methodology to estimate emissions from nonroad equipment. This methodology implements the OFFROAD model. It takes into consideration the effects of regulation, technology types and seasonal conditions on emissions. The model estimates emissions in units of tons per year by multiplying emission factors, population of each item of equipment, maximum horsepower, load factor, and annual activity in hours per year (MSEI, 2007). Similarly, to the NONROAD model, the methodology developed by CARB considered steady-state engine, which failed to reflect the actual operation of construction equipment.

The Sacramento Metropolitan Air Quality Management District developed a model called URBEMIS2007 that estimated the emissions of any air pollutant from land development projects. The model allowed a user to estimate construction emissions during the demolition, fine site grading, mass site grading, trenching, building construction, architectural coating and paving. The developed model estimates construction emissions based on project size, and equipment used, and emission factors (URBEMIS, 2007). The limitation associated with the model is that it assumes that heavy construction takes place on approximately 25% of the project size at one time and uses limited number of equipment that can be included in the analysis (Lewis, 2009).

2.10.8 Contribution of Lewis' Study

The work conducted by Lewis (2009) raises the awareness of pollution from construction equipment. More specifically, his work encourages the following activities (Lewis, 2009):

1. Determine the effects on emission from alternative fuels when used in construction equipment.

2. Modify construction equipment operation procedures to decrease fuel use and production of pollutants.

3. Investigate technological controls for construction equipment that will reduce air pollutant emissions.

4. Develop green fleet certification programs that take into account real-world factors that prevent or reduce emissions.

Lewi's work demonstrated the high impact that mechanical attributes have on the production of pollutants but also the difficulties associated with having limited databases the fail to consider the may types of equipment that are available to the industry. Nevertheless, the data collected in his work allowed him to create emission estimates that consider varying engine loads during operations of a piece of equipment. Therefore, Lewis' contribution is establishing a methodology that reliably estimates fuel use and emissions for construction projects in the same manned that other common construction metrics are estimated.

CHAPTER 3: Framework for Equipment Cost Analysis in Construction.

The framework introduced in this chapter is intended to serve as a guideline for construction managers to evaluate construction equipment considering environmental criteria.

3.1 Introduction

Over the last two decades, there has been a significant reduction in emissions generated by North America's construction industry (Park et al., 2003). One of the primary factors that have led to the cutback is the incorporation of government regulations such as the National Environmental Policy Act of the United States and the Environmental Protection Act of Canada (Boyd, 2016; Sinha & Jha, 2017). The implementation of these regulations has shown that proper construction management is associated with low energy consumption (Park et al., 2003). The construction industry is one of the focal points of environmental regulation, as reports published by the EPA's Clean Air Traffic Scientific Advisory showed that 40% of total CO2 emissions are generated by construction equipment (Li & Lei, 2010). The commitment of governments to reduce negative impacts on the environment and the significant influence of the construction industry reflects the need for planning tools that may maximize the operation's efficiency while promoting sustainability.

Some examples of tools that have been developed to reduce emissions are the implementation of planning frameworks in the construction industry. Jassim et al. (2016) developed a model that helped project managers assess the energy consumption and CO2 emissions of mass haulers. Carmichael et al. (2012) proposed procedures that reduce hauling emissions by changing fleet size, truck size, haul schedule and haul route. Peña-Mora et al. (2009) implemented emissions estimating models to determine which construction method provides the best performance and lowest emissions.

This chapter formalizes an integrated framework for equipment cost analysis based on simulation models and environmental assessments, such as Lewis' (2009) methodology to estimate fuel use and emission rates of construction equipment. The formalized framework aims to help construction managers assess environmental impacts created by distinct fleet configurations in order to select the most efficient equipment combination.

3.2 Fleet Management

The increasing costs of buying and operating equipment are changing how construction companies manage their fleets (Radosavljevic & Bennet, 2012). As these organizations suffer from budget constraints and rising costs, managers are demanded to use tools and strategies to efficiently solve the obstacles faced in fleet management. These obstacles include inappropriate use of equipment, managing routine, emergency maintenance, and replacing old equipment by purchasing new ones (Radosavljevic & Bennet, 2012).

The most efficient way to optimize earthwork equipment operations is through good Fleet Management (FM). Proper Fleet Management minimizes risks associated with inappropriate use of equipment, improves efficiency, reduces unnecessary costs and ensures compliances with the scope of work designated (Gransberg et al., 2006). Nevertheless, proper Fleet Management is a complicated process that requires various tools to make productive use of equipment while extending equipment life.

3.3 Fleet Management Problems

The problems faced in fleet management can be divided into three main groups: Efficiency and productivity of the equipment, high operational costs, and environmental concerns (Abdi & Taghipour, 2018).

3.3.1 Efficiency and Productivity

Since construction equipment is an asset whose value is equivalent to the amount of work produced during their lifetime, owners need to ensure that the machinery is maintained correctly, but that work is also completed on time. Thus, equipment that is not continually working is a monetary loss for the owners.

To reduce the waste of time and increase equipment productivity, many companies have implemented Global Positioning Systems (GPS) and Global System for Mobile Communications (GSMC) (Saghaei, 2016). These are tracking systems that allow users to know the current or past locations of a machine at any given time and inform on hours that were spent on a specific task.

Another aspect that affects the productivity of fleet equipment involves transportation and logistics. Managers seek to increase equipment productivity while minimizing overall cost by setting efficient planning and routing of fleet operations to allow tasks to be completed at a higher pace. Although many tools have been developed to address this issue, efficient planning and routing remain a judgement call on the manager.

3.3.2 Operational Costs

Beyond having a high acquisition cost, the use of construction fleet equipment has a high operational cost. Fuel, tires, repairs, and lubricants are some of the frequently paid items for over the lifetime of a machine. A few of these items are also continually fluctuating in price and are affected by different economic factors (Mishra & Regmi, 2017).

According to the American Transportation Research Institute (2018), another significant aspect of operational costs is operator salaries, dependent on the project, which can represent up to 26% of a fleet's total operational costs. Operators are a peculiar element since they carry a tremendous responsibility in the equipment's safe operation and avoid the high costs associated with accidents.

3.3.3 Environmental Concerns

The environmental concerns created by the use of heavy equipment in construction are pollution in the form of air, noise and water. Since construction equipment is powerful machinery that mostly requires diesel, their engines emit waste gas containing gaseous pollutants and liquid contaminants (Marzouk et al., 2017). The most common and harmful pollutants emitted are a series of carbon oxides and sulphides produced due to diesel's insufficient combustion process. Also, harmful particles of sulphate and nitrate are produced during the combustion process, which are substances that increase the rates of cancer and respiratory diseases (Perera, 2017).

Noise pollution refers to loud and annoying noises generated in the operation process of construction machinery (Marzouk et al., 2017). This pollution harms the environment and ecological nature of a site. Likewise, contamination of water has negative impacts on the ecological nature of a site. This type of pollution is caused by large quantities of water used for specific construction processes and is allowed to be introduced into the ground, although the water should not be used for any other purposes and should be disposed of appropriately (Zhang, 2015).

3.4 Development of Framework

Today, it is critical for the construction industry to evaluate greenhouse emissions as a cost factor in construction planning, equipment selection and cost estimating due to the importance of preventing further environmental decay. Hence, the objective of the framework, shown in Figure 3-1, is to assist construction managers to select the most sustainable fleet available. A sustainable fleet represents an equipment combination that reduces the time spent in non-productive activities (such as idling and waiting) and minimizes the production of emissions while delivering a high production rate.

The proposed framework is based on lean thinking and green construction principles, which were explained in detail in Chapter 2. In order to accomplish an efficient and environmentally friendly construction system, the framework adopts the utilization of simulation models and quantitative methods to assess emissions.

As seen in Figure 3-1, the framework is divided into two components: Lean Operation and Green Operation. The Lean Operation component is used to select equipment and plan work by implementing lean construction concepts, such as reducing idle time and eliminating unnecessary tasks. The resulting fleet configuration based on this component produces a higher operation efficiency and better assets utilization but will not necessarily provide a fleet configuration that attains a high performance in connection with greenness and sustainability.

The Lean Operation component uses as a basic principle the concept of fleet balancing. Fleet balancing aims to realize the full capabilities of a particular piece of equipment by allowing it to set its productivity as high as possible in a particular environment. This equipment governs the construction system and is referred to as the leading resource. The other pieces of equipment that make up the construction system are set to match the leading equipment's production rate. In most instances, overcapacity on the production rate of supporting equipment is allowed to ensure that the leading resource does not experience idling or waiting time, thus allowing it to operate at its full production capacity. Overall, the use of the Lean Operation component in the Framework improves a construction system's operation efficiency by maximizing the utilization of equipment, labour, and time while minimizing the amount of waste on the system.

On the other hand, the Green Operation component enables the framework to consider greenhouse gas emissions as a type of waste, a financial item and a performance indicator. Consequently, the Green Operation component uses quantification methods to estimate the fuel use rate of construction equipment and determine the amount of pollutants emitted.

The framework bases its Green Operation component on the quantification methods proposed by Lewis (2009) during his work as a Ph.D. student under the supervision of Dr. William Rasdorf. Lewis' work is distinct to previously established estimating methods, as they are based on steady-state engine parameters and lacked field observations. Lewis successfully created mathematical equations that relate energy use and emission from construction equipment via the collection of field data and the consideration of mechanical attributes of the equipment that may impact pollutants' production. Additionally, the methodology proposed by Lewis allows emissions to be quantified as a cost factor and become a performance indicator in terms of unit cost ($/g), which links both "Lean" and "Green" operations of the framework and allows a comprehensive evaluation of alternative fleets in equipment selection and work planning.

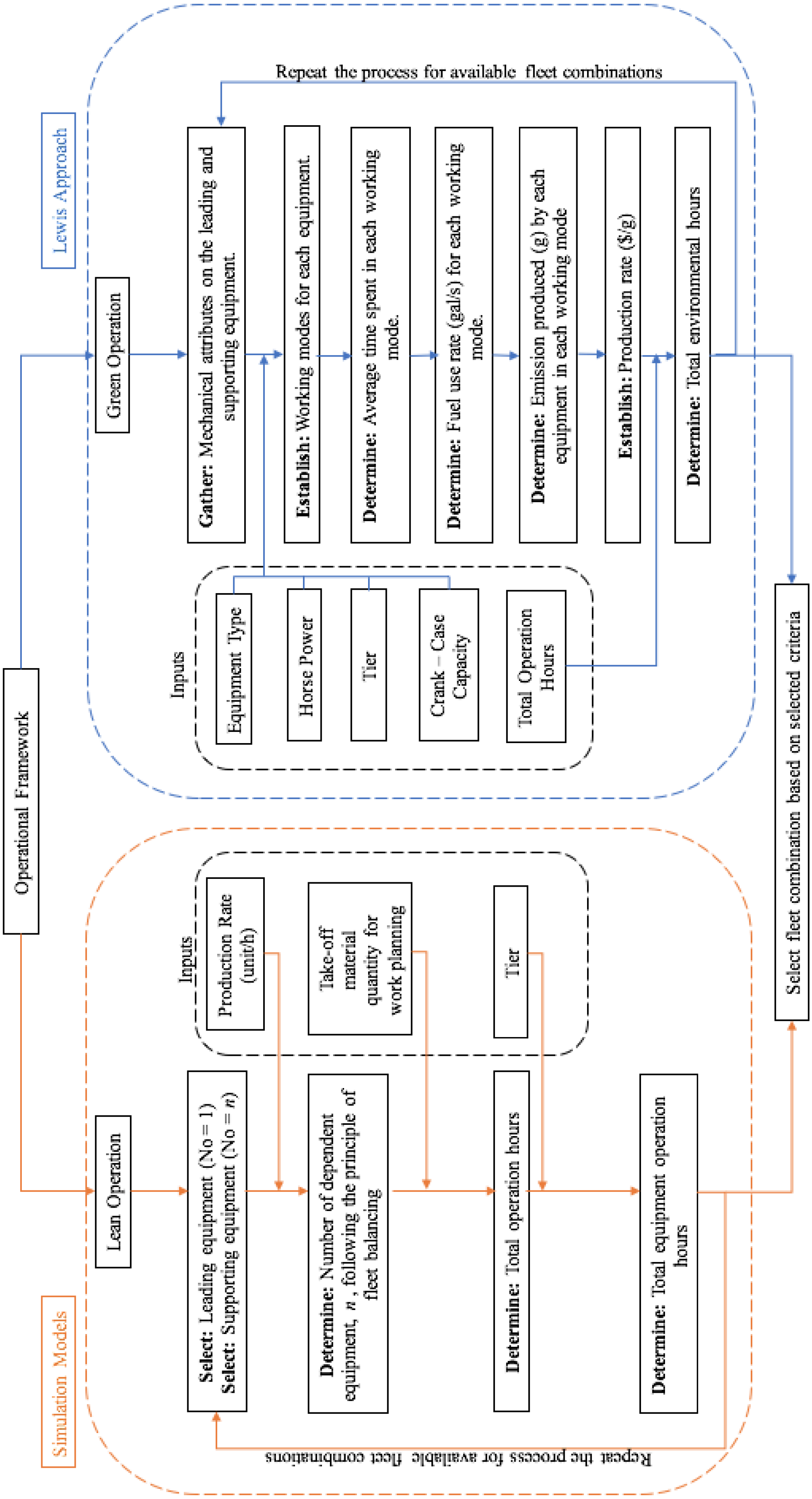

Figure 3-1. Applicable Framework for Equipment Selection via Costs Analysis and Environmental Assessment

In order to use the Framework, the following steps should be followed:

1. Select leading equipment and supporting equipment: from all the equipment involved in the construction operation, leading equipment must be selected. This leading equipment will govern the construction system by setting the production rate. Simultaneously, the supporting equipment assists in completing the tasks by matching the system's productivity rate

2. Set the production rate of the construction system: the system's production rate can be determined through the application of DES programs such as SIMPHONY. It is critical for this DES to accurately represent the process of operations in terms of equipment involved and cycle times to complete tasks

3. Takeoff material quantity for work planning: This step can also be accomplished by simulation models or by taking field

4. Determine total operation hours: The total operation hours can be obtained through the use of simulation models.

5. Conduct Lewis methodology to estimate fuel use (gal/hr) and emission rates (g/hr):

    5.1. Identify and quantify equipment attributes that affect fuel use and emission rates (Equipment type, engine size, engine age, engine load, and engine tier).

    5.2. Perform an engine modal analysis for each type of equipment.

    5.3. Develop engine modal fuel use and emission rates for each engine mode through evaluation of field measurements data.

    5.4. Determine time spent in each engine mode and fraction of fuel used in each engine mode through the study of representative duty cycles.

5.5. Establish the weighted-average fuel use rate by multiplying the modal fuel use rate by the fraction of time spent in each engine mode.

5.6. Establish the weighted average emission rate for each pollutant by multiplying the modal emission rate for each engine mode by the fraction of fuel used in each engine mode.

5.7. Convert the mass per fuel used weighted-average emission rate to a mass per time weighted-average emission rate.

6. Establish an hourly rate for equipment operation and an emission fee: The hourly rate of equipment operation depends on the type of equipment being used and the rate for the operator. For emissions, a fee for the production of emission ($/g) needs to be established, so the vehicle's emissions rates can be used as a performance indicator. The quantification of the fuel use rate (gal/hr) and emissions rate (g/hr) is obtained through Step 5.

7. Determine the total operational and environmental cost.

8. Evaluate different fleet combinations by repeating the steps (1-7).

9. Select fleet combination: Once all the fleet combinations have been analyzed, it is possible to select the fleet combination based on specified criteria, whether it is the most environmentally-friendly combination, or the fleet associated with the lowest operational cost, or a trade-off between both.

CHAPTER 4: Application of Framework in Common Construction Processes.

This section introduces the current practices to mitigate the environmental impact of construction equipment and showcases the developed framework's implementation in a simplified construction process. The use of a simplified construction process will also prove the concept of and demonstrate clearly how the combination of simulation models and quantification techniques of emissions, such as Lewis's, can serve as a tool to reduce emission from construction equipment.

4.1 Current Practices to Mitigate Environmental Impacts of Construction Equipment.

The use of construction equipment represents an extensive production of pollutants harmful to human health and the environment (Guzder, 2019). Due to the growing concern about the environment's decay and economic instability of the past decade, the implementation of sustainable methods into engineering procedures has expanded (Poveda, 2017). This section introduces the current practices to reduce emissions from construction equipment and presents the application of simulations models and environmental assessments into the Operational Framework.

Over many years, industries have implemented regulations that seek to reduce the negative weight their operations have on the environment. An example of such regulation is the Canadian Protection Act of 1999, which aims to make pollution prevention the priority approach to environmental protection (Government of Canada, 2000). As a result, it has made construction equipment a focused point in the industry towards cleaner operations. As of today, strategies and devices have been developed and implemented to construction equipment in order to achieve this goal. Some of these devices and strategies that have had substantial results are as follow:

- Use of Diesel Particulate Filters: The use of catalyzed diesel particulate filters reduces particulate matter production from the exhaust of earthwork equipment. These filters reduce the temperature at which collected diesel particulate matter oxidizes. They can either be directly incorporated into the filter system or added to the fuel as a fuel-borne catalyst (Environmental Protection Agency of the United States, 2008).

- Use of Fuel-Borne Catalyst: This catalyst is used to reduce nitrogen oxides, particulate matter and nitrogen monoxide emissions from earthwork equipment. These products contain a fuel modification catalyst that changes diesel fuel composition immediately before its use in an engine. (Linak et al., 2013).

- Use Diesel Oxidation Catalyst: Uses a catalytic substance to accelerate chemical reactions. When gases emitted through exhaust contact the catalyst, the residual hydrocarbons and carbon monoxide are oxidized (Environmental Protection Agency of the United States, 2008).

- Ensure Catalytic Converters Efficiency: Catalytic converters are used in gasoline-powered engines to reduce carbon monoxide and nitrogen oxides. They operate by changing these gases to carbon monoxide, nitrogen, oxygen and water (Linak et al., 2013).

- Evaluate Alternative Technologies to Reduce Emissions from Engines: There are a high number of emission control technologies that are being developed. Some of them are selective catalytic reduction technology, exhaust gas recirculation routing, and a lean nitrogen monoxide catalyst (Kozina et al., 2020).

- Properly Maintain Engines and Exhaust Systems: Maintaining equipment engines reduces exhaust emissions of carbon monoxide and particulate matter. Equipment that is poorly maintained will have higher emissions and higher consumption of fuel (Kozina et al., 2020).

- Consider Alternatives for Heat and Air Conditioning for Off-Road Vehicles: Currently, there are multiple alternatives to the provision of heat/air condition through idling. Some of these alternatives include the use of auxiliary power systems and onboard electrification (Kozina et al., 2020).

4.2 Emissions Mitigation Through Developed Framework.

The developed Framework introduced in Chapter 3 focuses on the utilization of modelling systems and quantification techniques. Throughout this work, the modelling of construction systems is performed using SIMPHONY, a special-purpose simulation tool designed to model construction systems. A general overview of the utilization of SIMPHONY can be found in Appendix A.

The use of simulation modelling is a powerful technique to assist construction managers in decision making (AbouRizk & Mohamed, 2001). Unfortunately, accurate modelling of a construction process is a complex task since every construction project has a high degree of uncertainty and variability, such as weather conditions and worker availability. Nevertheless, the use of simulation models has the ability to optimize construction processes and obtain a better understanding of construction alternatives in a system.

SIMPHONY was selected as the modeling tool for this work due to its Special Purpose Simulation (SPS) trait. This trait allows the program's operation by users who are knowledgeable in a given domain but not necessarily in a simulation (AbouRizk and Mohamed, 2001). Still, SIMPHONY has the ability to evaluate highly complex systems while supporting graphical, modular, and integrated modelling (AbouRizk et al., 2016).

As a result of the need to reduce emission and energy consumption during construction projects, there has been a growing interest in developing techniques to lower these items. At the same time, there has been a focus on developing the ability to effectively assess the consumption of energy and production of pollutants in today's industries (Gielen et al., 2019). However, many studies have estimated environmental impacts from construction without collecting and processing accurate field data (Giunta, 2020; Švajlenka, J., & Kozlovsk, 2020; Larasati et al., 2019). Therefore, practical and field-based methods to quantify energy consumption and emissions of construction equipment are essential in the environmental assessment of construction equipment.

The methodology proposed by Lewis was selected to determine the environmental impacts of pollutants from construction equipment since it is based on in-use field data measurement to assess emissions (Lewis, 2009). Lewis developed a scientific methodology that functions in the same manner as other common construction estimates. Although it is possible to measure the quantities of fuel used and pollutants emitted by construction equipment during operations, it is not always practical. Therefore, using the methodology proposed by Lewis, or any other practical estimating method, allows construction managers to easily estimate the impact that fleet configuration may have on their project's economic and environmental aspects (Lewis, 2009).

In order to introduce the application of the framework in a general context, the emissions of pollutants in a simplified earthmoving operation are evaluated. An earthmoving operation is a very common construction process that usually involves a large amount of heavy equipment and the interaction of multiple resources (personnel, equipment, weather conditions, etc.) (Rodriguez, 2019). Additionally, it tends to be the repetitions of equipment cycles that have a specific productivity. This productivity depends heavily on uncertainties that make it difficult for construction managers to create reliable estimates (AbouRizk et al., 2016).

In the earthmoving model, shown in Figure 4-1, a contractor is responsible for hauling 2000 bank cubic meter (BCM) of soil from one location to another. In this model, an excavator digs out a finite volume of dirt and places it in a dirt pile, followed by a front-end loader picking up dirt from the pile and placing it onto waiting trucks. Once a truck has been fully loaded, it then travels to the dumpsite where it drops its cargo, and it then travels back to the excavator's location. This process occurs on multiple repetitions until all 2000 BCM of soil has been hauled. Figure 4-2 shows the schematic of the earthmoving operation modelled.

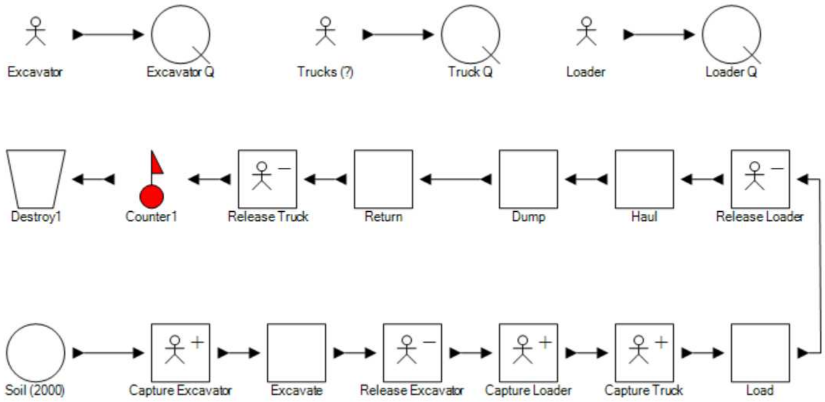

Figure 4-1. Simplified Earthmoving Model.

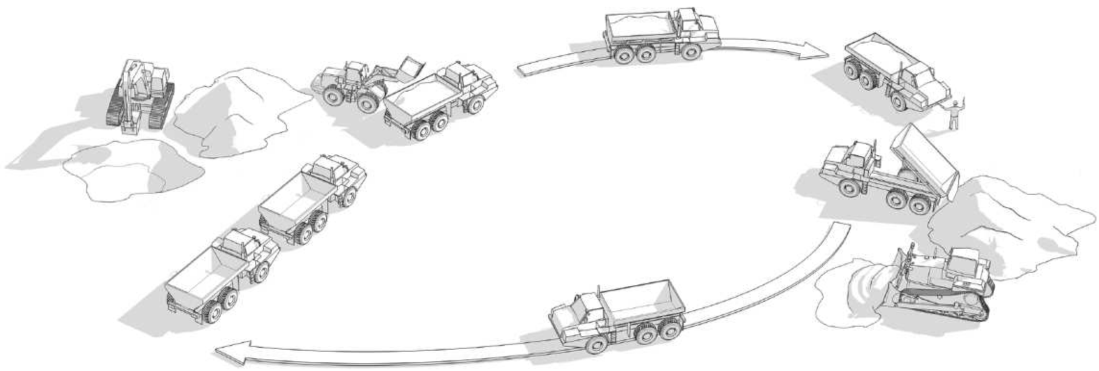

Figure 4-2. Schematic of Earthmoving Operation. Reprinted from *Construction Simulation: an Introduction Using Simphony* (p 156) by AbouRizk et al., 2017, University of Alberta.

During the planning of the earthmoving operations, the contractor decides that his fleet will be composed of one excavator, one loader and an undetermined number of trucks. His goal is to select a fleet combination that will reduce the associated cost and will also limit the amount of pollutants created in the process.

In order to determine the best fleet configuration, the steps outlined in the developed Framework can be carried out:

Step 1: Select leading equipment and supporting equipment.

The initial step of the developed framework relates to the principle of lean operations and fleet balancing. For instance, "lean" construction has a production system to minimize waste of material, time, and effort in order to generate the maximum possible amount of value (Koskela et al., 2000). For construction processes that utilize vehicles, a lean system is provided through the application of fleet balancing. To accomplish the full potential of a particular piece of equipment, its productivity is set to drive the system's productivity. This piece of equipment is referred to as the 'leading resource,' and other supportive equipment will help match the system's productivity.

Nevertheless, to ensure the leading resource operates at its full capacity without idling or delays, the productivity of the modelled system is set up to be controlled by the leading resource. For example, in the simplified earthmoving model, the loader is set to be the leading resource by limiting the number of resources to one, as shown in Figure 4-3. Therefore, the loader will govern the system's production, while the trucks would serve as the supportive equipment. As the loader will set the system's productivity, the number of trucks used need to be rounded up to assure the loader works at its highest capacity (Peurifoy & Oberlender, 2014).

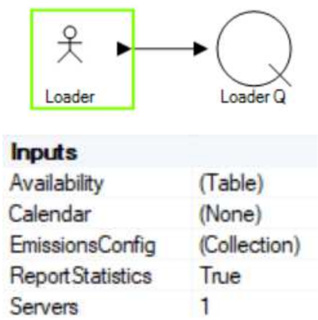

Figure 4-3. ‘Leading’ Resource of Simplified Earthmoving Model.

Overall, in the simplified earthmoving model the loader was set as the ‘leading resource’ while the trucks were set as the ‘supportive resources’.

Step 2: Set the production rate of the construction system:

A significant benefit of developing simulation models is their quick ability to determine the analyzed system's basic characteristics. In the case of SIMPHONY, uses the following analytical methods or a combination of them (Abourizk & Mohammed, 2001):

- Simulational behaviour: This trait allows for the definition of resources, files, events and entities of a given element, and the performance of specified tasks.
- Statistical behaviour: Allows for the collection of information acquired through the simulation process. This data includes resource utilization, queue length and cycle times.
- Planning behaviour: Defines how a developed modeling element transforms results into a project plan that may include production, resource utilization, revenue forecast and a schedule.

For the simplified earthmoving model, SIMPHONY provides the general results shown in Tables 4-1 and 4-2. These results are obtained by considering the use of four trucks and two trucks, respectively. As shown in these tables, SIMPHONY is able to determine the time at which the first and last cycle was completed, the average utilization for each piece of equipment, the average and maximum time that each piece of equipment was idling, and the whole productivity of the system. In this case, a system with four trucks has a productivity of 0.109 truckloads/minute, and a system with two trucks has a productivity of 0.055 truckloads/minute.

Table 4-1. General Results from SIMPHONY - Using Four Trucks.

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Scenario1 (Termination Time)	1,831.000	0.000	1.000	1,831.000	1,831.000

Counters

Element Name	Final Count	Production Rate	Average Interarrival	First Arrival	Last Arrival
Counter1	200.000	0.109	8.970	46.000	1,831.000

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
Excavator (Inner Resource)	54.6%	49.8%	100.0%	0.0%	2.000
Loader (Inner Resource)	97.9%	14.4%	100.0%	0.0%	1.000
Trucks (?) (Inner Resource)	98.3%	10.9%	100.0%	0.0%	4.000

Waiting Files

Element Name	Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
Excavator Q	54.069	65.190	198.000	0.000	495.000
Loader Q	43.205	26.066	89.000	0.000	395.540
Truck Q	0.214	0.410	1.000	0.000	1.960

Tables 4-2. General Results from SIMPHONY - Using Two Trucks.

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Scenario1 (Termination Time)	3,617.000	0.000	1.000	3,617.000	3,617.000

Counters

Element Name	Final Count	Production Rate	Average Interarrival	First Arrival	Last Arrival
Counter1	200.000	0.055	17.945	46.000	3,617.000

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
Excavator (Inner Resource)	27.6%	44.7%	100.0%	0.0%	2.000
Loader (Inner Resource)	98.9%	10.3%	100.0%	0.0%	1.000
Trucks (?) (Inner Resource)	99.5%	6.1%	100.0%	0.0%	2.000

Waiting Files

Element Name	Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
Excavator Q	27.371	53.685	198.000	0.000	495.000
Loader Q	70.755	41.876	143.000	0.000	1,279.610
Truck Q	0.602	0.489	1.000	0.000	10.890

Step 3: Take-off material quantity for work planning.

As of today, the common practice of the construction industry is to perform quantity take-offs by analyzing blueprints and other types of 2-D plan sheets (Olsen & Taylor, 2017). Estimators need to review every single sheet of the project plans in order to determine the amount of material and work required to complete the project. In addition to account for material and work needed, estimators also need to consider waste factors, which is a process that is time-consuming and relies its accuracy on the judgment of the estimator. In recent years, the construction industry has been shifting into the implementation of other estimating methods. Some of these methods include the use of simulation models such as Building Information Modeling (BIM) and BIM-based quantity take-off. (Olsen & Taylor, 2017).

BIM is a model-based process that allows the construction industry members to plan, design, build, and manage projects in a more efficient manner (Autodesk, 2020). The most popular programs associated with this process include Autodesk Revit, Vico, Assemble, Bentley and Autodesk Civil 3D. Many of these programs allow the creation of three-dimensional models that have the ability to link individual elements that make up the construction system. As the models that can be developed in these programs can carry a high degree of data, these programs can quickly produce quantity take-offs with a high degree of accuracy. However, the use of BIM estimates also finds the following limitations (Kim et al., 2019):

- Although BIM has gained popularity, it still lacks general acceptance from industry members leading to insufficient knowledge and understanding to effectively use BIM due to contractual, legal and technological challenges.

- Lack of ability to share data among other programs that are widely used in the industry, such as Excel.

- Challenges in clearly defining the relationship between cost data and building elements.

For the purpose of this work, the use of BIM to perform work and material takeoff was not utilized. Instead, the amount of work and material associated with each sample project is assumed. For the simplified earthmoving operation, 2000 bank cubic meters (BCM) of soil need to be transported. Nevertheless, the use of BIM is encouraged in real-case scenarios.

Step 4: Determine total operation hours.

The principles of Lean Thinking are attributed to Taiichi Ohno, a Japanese industrial engineer and father of the Toyota Production System (Ohno & Ohno,1998). Ohno’s goal was to craft the entire production system of vehicles so mass production increased while unnecessary use of materials and labour were reduced. Today, Lean Thinking has been embraced in industries that go beyond the manufacturing of products. One of these industries is construction. Lean construction aims to better meet customer needs by:

- Identifying and delivering value to the customer, by eliminating anything that does not provide value to the customer.

- Organizing the construction system so it can behave in a continuous flow.

- Delivering efficient and reliable projects by making the necessary alterations during construction periods.

- Delivering a project in a timely manner.

In order to accomplish the goals set in lean construction, industry members have adopted the use of tools that provide a better understanding of a project's characteristics and processes. One of these tools is the application of computer simulations. A simulation model is able to analyze the uncertainties at a detailed level and determine their overall impact on the objectives of a project. Through simulation, a user is also able to compare between construction alternatives, determine the system performance under different conditions and resources, perform a sensitivity analysis to determine the factors that have the most significant impact on the performance of the system, determine bottlenecks, and study relationships between resources (AbouRizk & Mohamed, 2001).

Two types of simulation models are commonly used in the construction industry: General purpose simulation (GPS) or Special purpose simulation (SPS). GPS is a discrete-time simulation that analyzes set parameters to determine whether a system meets established criteria. In the case of the model not being acceptable, the simulation process is reiterated, and a new alternative system is evaluated until an adequate system is found (AbouRizk & Mohamed, 2001) With SPS, a platform or a template is created for a specific application. This platform follows the same evaluation process as GPS, but instead of building a new system, only the pre-defined system's input parameters can be altered. The initial characteristics and behaviour of the system remain unchanged (AbouRizk & Mohamed, 2001).

This simulation model created for the simplified earthwork model, seen in Figure 4-1, falls under the GPS classification as it is a discrete event simulation. The use of SIMPHONY allowed determining the productivity of each case and the total time required to complete operations, as seen in Table 4-1 and Table 4-2. In this case, a system with four trucks has a total operation time of 1831 min (30.5 hours), and a system with two trucks has a total operation time of 3617 min (60.3 hours).

For the development of the simplified earthwork model, seen in Figure 4-1, the inputs include: number of resources, duration for each activity, and productivity of the system modelled. These values are constant in order to perform a simple assessment of earthwork operation. In the study of a more complex system, the speed of trucks and emission rate are values that change throughout the completion of a project due to the varying conditions that are commonly seen in the field. The case study in chapter 5 demonstrates the application of stochastic inputs in more complex earthwork processes.

Step 5: Conduct Lewis methodology to estimate fuel use (gal/hr) and emission rates (g/hr).

The methodology to estimate fuel use and emission rate established by Lewis was explained in detail in Chapter 2. In order to incorporate Lewis's methodology in the simplified earthwork model, the following steps need to be followed:

5.1 Identify and quantify equipment attributes that affect fuel use and emission rates:

As the simplified earthwork model evaluates two fleet configurations that differentiate by the number of trucks put in service, the only attributes that need to be considered are those pertaining to the truck, such as equipment type, engine size, engine age, engine load, and engine tier. For this case, we will assume the trucks have the following traits:

- Equipment type: Truck

- Engine Size: 99-88 horsepower and 4.5 - 3.9 liters of displacement range.

- Engine Age: 10+ year engine; therefore, an efficiency factor of 0.75 will be assumed.

- Engine Load: Manifold Absolute Pressure (MAP) of the engine varies depending on the activity performed by the equipment. Therefore, it is necessary to normalize MAP values through the engine modal analysis.
- Engine Tier: Tier 2.

5.2 Perform an engine modal analysis for each type of equipment.

As explained in section 2.9.4, the modal analysis is performed to categorize data based on what the piece of equipment is doing, such as idling or working. In the case of a hauling truck, the activities can be categorized into 'idling', 'moving', 'hauling', and 'dumping'. Due to the lack of field measurements for the simplified earthwork model, only the results from the modal analysis on fuel use rate and emissions of CO obtained from Lewis' study are applied to this case. Figure 4-4 shows the fuel use rate data as a function of activity modes for a hauling truck obtained from field measurements. Figure 4-5 shows CO emissions as a function of activity modes for a hauling truck obtained from field measurements.

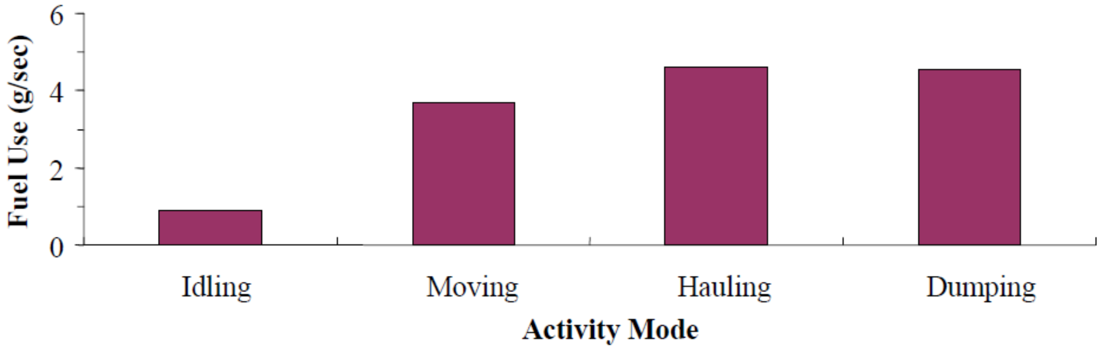

Figure 4-4. Results from Activity Mode Analysis on Fuel Use Rate for Off-Road Truck. *Reprint from Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

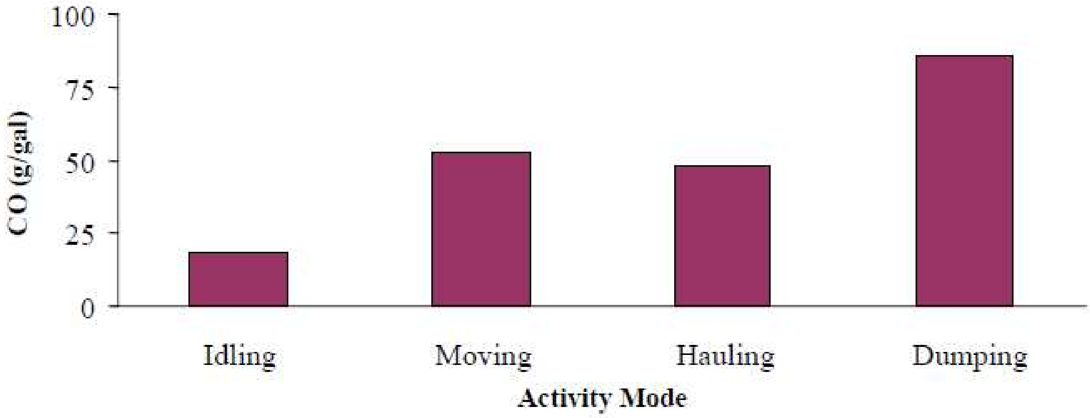

Figure 4-5. Results from Activity Mode Analysis on CO emissions for Off-Road Truck. *Reprint from Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

5.3 Develop engine modal fuel use and emission rates for each engine mode through data evaluation of field measurements.

The engine modal analysis categorizes data based on a range of engine loads imposed on the engine. In every case, values of MAP are normalized to create ten engine modes. The engine modal analysis, fuel use and emission rates are quantified by arranging the second-by-second data into engine mode categories and then calculating the average fuel use and emission rates for each of them. Due to lack of field measurements for the simplified earthwork model, only the engine analysis results on fuel use rate and emissions of CO obtained from Lewis's study are applied to this case. Figure 4-6 shows the fuel use rate data as a function of activity modes for a hauling truck obtained from field measurements. Figure 4-7 shows CO emissions as a function of activity modes for a hauling truck obtained from field measurements.

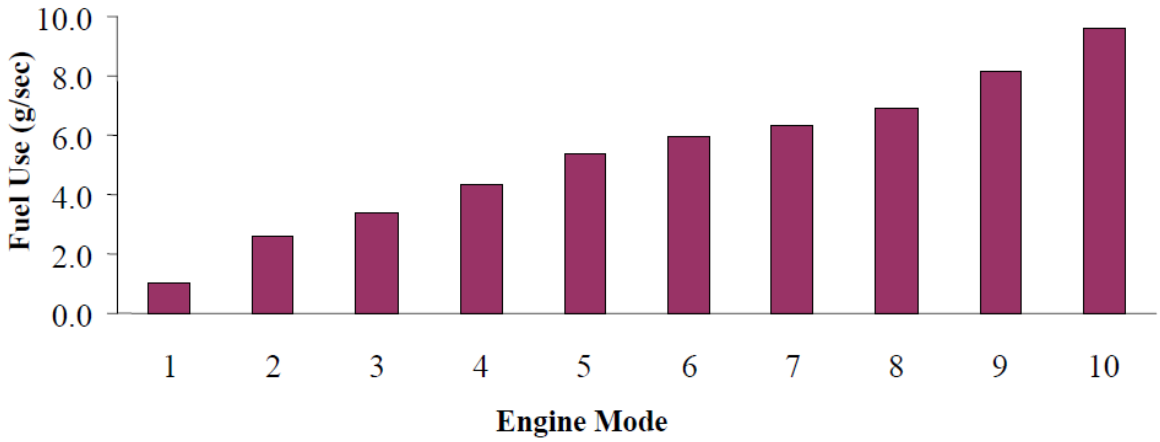

Figure 4-6. Results from Engine Mode Analysis on Fuel Use Rate for Off-Road Truck. *Reprint from Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

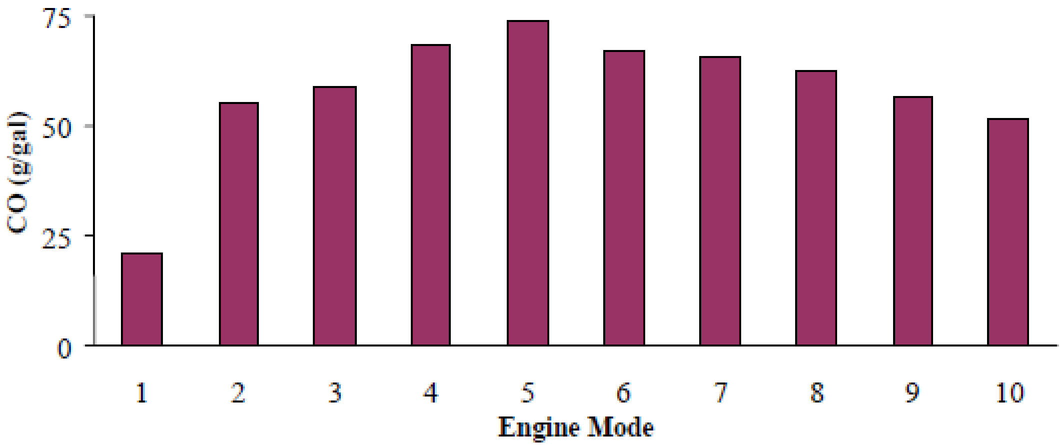

Figure 4-7 . Results from Engine Mode Analysis on CO emissions for Off-Road Truck. *Reprint from Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles*. By Lewis, Michael P., 2009 by University of North Carolina.

5.4 Determine time spent in each engine mode and fraction of fuel used in each engine mode through the study of representative duty cycles.

Taking a significant amount of field data, as performed by Lewis, enables to determine the time spent in each engine mode. Although this is an impractical method due to its time-consuming, expensive nature, it is possible to approximate the time spent using the analytical properties of simulation models. It is possible to include user-written code that evaluates different conditions in a construction environment that may affect the amount of time spent in a specific engine mode. This user-written code is demonstrated in the case study presented in Chapter 5. For the simplicity of this sample earthwork model, no user-written code is included, and analyzed; instead, trucks are assumed to be running in all engine modes at an equal amount. For example, if trucks are put in use for 1,000 minutes, then the truck spends 100 minutes in each engine mode.

5.5 Establish the weighted-average fuel use rate by multiplying the modal fuel use rate by the fraction of time spent in each engine mode.

By multiplying the average fuel use rate per engine mode, shown in Figure 4-6, by the fraction of time spent in each activity and a conversion factor (1.132 to convert g/s to gal/hr), it is possible to determine the average fuel use as a function of time. Table 4-3 exhibits the weighted-average fuel use rate for the simplified earthwork model:

Table 4-3 . Weighted-Average Fuel Use Rate for Simplified Earthwork Model with Two Trucks.

		Activity Fraction of Time				Weighted Fuel Use (g/s)			
Mode	**Modal Fuel Use (g/s)**	**Idling**	**Moving**	**Hauling**	**Dumping**	**Idling**	**Moving**	**Hauling**	**Dumping**
1	0.63	0.39	0.77	0.65	0.39	0.2457	0.4851	0.4095	0.2457
2	1.39	0.1	0.06	0.07	0.1	0.139	0.0834	0.0973	0.139
3	1.99	0.07	0.04	0.05	0.07	0.1393	0.0796	0.0995	0.1393
4	2.54	0.07	0.03	0.04	0.07	0.1778	0.0762	0.1016	0.1778
5	2.98	0.08	0.03	0.04	0.08	0.2384	0.0894	0.1192	0.2384
6	3.45	0.07	0.02	0.03	0.07	0.2415	0.069	0.1035	0.2415
7	3.96	0.05	0.01	0.03	0.05	0.198	0.0396	0.1188	0.198
8	4.49	0.05	0.01	0.03	0.05	0.2245	0.0449	0.1347	0.2245
9	5.08	0.05	0.01	0.03	0.05	0.254	0.0508	0.1524	0.254
10	5.63	0.07	0.01	0.03	0.07	0.3941	0.0563	0.1689	0.3941
				Fuel wt.avg (g/s)		2.2523	1.0743	1.5054	2.2523
				Fuel wt.avg (gal/hr)		2.55	1.22	1.70	2.55

5.6 Establish the weighted average emission rate for each pollutant by multiplying the engine mode's modal emission rate by the fraction of fuel used in each engine mode.

The weighted-average emission rate can be calculated by multiplying the average emission rate, exhibited in Figure 4-7, by the fraction of time spent in each activity. Table 4-4 shows the weighted-average emission of CO for the simplified earthwork model:

Table 4-4. Weighted-Average Emission of CO for Simplified Earthwork Model with Four Trucks.

		Activity Fraction of Time				Weighted Emission Rate (g/gal)			
Mode	Modal Emission (g/gal)	Idling	Moving	Hauling	Dumping	Idling	Moving	Hauling	Dumping
1	20	0.39	0.77	0.65	0.39	7.8	15.4	13	7.8
2	55	0.1	0.06	0.07	0.1	5.5	3.3	3.85	5.5
3	60	0.07	0.04	0.05	0.07	4.2	2.4	3	4.2
4	70	0.07	0.03	0.04	0.07	4.9	2.1	2.8	4.9
5	74	0.08	0.03	0.04	0.08	5.92	2.22	2.96	5.92
6	66	0.07	0.02	0.03	0.07	4.62	1.32	1.98	4.62
7	65	0.05	0.01	0.03	0.05	3.25	0.65	1.95	3.25
8	63	0.05	0.01	0.03	0.05	3.15	0.63	1.89	3.15
9	58	0.05	0.01	0.03	0.05	2.9	0.58	1.74	2.9
10	50	0.07	0.01	0.03	0.07	3.5	0.5	1.5	3.5
				Emission Rate wt.avg (g/gal)		45.74	29.1	34.67	45.74

5.7 Convert the mass per fuel used weighted-average emission rate to a mass per time weighted-average emission rate.

The results obtained in Table 4-3 and Table 4-4 can now be used to determine the weighted-average emission rate as a function of mass per time. To do so, multiply the weighted-average emission rate of CO (g/gal) by the weighted-average fuel use rate (gal/hr). Table 4-5 summarizes the weight-average emission rate of CO at each activity mode.

Table 4-5. Weight-Average Emission Rate of CO at Each Activity Mode.

	Acivity			
Pollutant	Idling (g/hr)	Moving (g/hr)	Hauling (g/hr)	Dumping (g/hr)
CO	116.619	35.389	59.082	116.619

Step 6: Establish an hourly rate for equipment operation and an emission fee.

The hourly cost for equipment and operation is dependent on the type of equipment being used. As the simplified developed model considers only two fleet configurations that differ in the number of trucks being utilized, the only cost difference will come from the use of these vehicles. In this case, the hourly rate for using the truck is $100/hr, and the driver rate is $35/hr.

A critical aspect of the framework is the application of appropriate emission pricing. As of today, there hasn't been established an accurate method to quantify emissions in a dollar value. Several public organization price emissions as a charge / tax against some variable that is closely related with production of pollutants (Plaut & Plaut, 1998). One problem with this method of pricing is the inability to effectively assess the relationship between emission and the activity correlated with emissions (Plaut & Plaut, 1998). For the purpose of this work, the fee for production of emission ($/g) is used as a performance indicator that is heavily based on judgement, but uses the pricing set by Samieadel and Golroo (2017) in their work "*Developing an Index to Measure Sustainability of Road Related Project Over the Life Cycle*". The cost rate for emission of each pollutant used in this work can be seen in Table 4-6.

Table 4-6. Set Prices for Each Type of Emissions.

Pollutants	Environmental Cost of Pollutants ($/g)
NOx	0.0061
HC	0.0053
CO	0.0081
CO_2	0.0406
PM	0.0122

Step 7: Determine the total operational and environmental cost.

To calculate the total operational and environmental cost, it is first necessary to obtain the total operation time and the time spent in each activity mode. The total operation time was obtained through simulation models' analytical tool, as shown in step 4. The use of models can also help identify the amount of time spent in each activity mode. The modeler must include the appropriate input to prompt the model to provide the information for each analyzed activity. An example of such input is shown in Chapter 5. Table 4-7 shows the total time spent in each activity for both truck combinations.

Table 4-7. Total Time Spent in each Activity.

Fleet Combination	Total Opeation Time (min)	Total Time per Activity (Min)			
		Loading/Idling	Hauling	Dumping	Moving/Returning
Fleet w/ four trucks	1831	348	769	201	513
Fleet w/ two truck	3617	687	1519	398	1013

When the model studies a fleet combination with four trucks, the total operation time is 1831 min. Throughout the whole process, the truck spent a total of 348 min loading/idling, 769 min hauling, 201 min dumping, and 513 min moving/returning. Nevertheless, the fleet combination with two trucks has a total operation time of 3617 min from which the truck spent a total of 687 min loading/idling, 1519 min hauling, 398 min dumping, and 1013 min moving/returning.

Once the amount of time spent per activity mode is calculated, it is possible to determine the total amount of pollutant emitted per activity mode. To do so, the Weight-Average Emission Rate at Each Activity Mode, shown in Table 4-5, needs to be multiplied by the Total Time Spent in each Activity Mode, shown in Table 4-7. The total amount of CO produced by each combination of trucks can be seen in Table 4-8.

Table 4-8. Total Amount of CO Produced.

Fleet Combination	Total CO Produced by Trucks (g)	CO Produced by Trucks per Activity (g)			
		Loading/Idling	Hauling	Dumping	Moving/Returning
Fleet w/ four trucks	9298	2705	1814	793	3986
Fleet w/ two truck	14060	2671	5905	1547	3937

Multiplying the set price for CO emissions, shown in Table 4-6, by the total amount of CO produced, shown in Table 4-8, will provide the environmental cost related to the use of different truck numbers. The difference in environmental costs between the two fleets can be seen in Table 4-9.

Table 4-9. Environmental Cost for Each Fleet Combination.

Fleet Combination	Total Environmental Cost ($)	Environmental Cost per Activity ($)			
		Loading/Idling	Hauling	Dumping	Moving/Returning
Fleet w/ four trucks	$75.32	$21.91	$14.70	$6.43	$32.29
Fleet w/ two truck	$113.89	$21.64	$47.83	$12.53	$31.89

Finally, to determine the operational cost, multiply the truck and driver rates by the total time of operations and the number of trucks involved. Table 4-10 displays the total operation cost for each fleet combination.

Table 4-10. Operational Cost for Each Fleet Combination.

Fleet Combination	Total Operational Cost ($)	Operational Cost per Activity ($)			
		Loading/Idling	Hauling	Dumping	Moving/Returning
Fleet w/ four trucks	$15,868.67	$3,015.05	$6,664.84	$1,745.55	$4,443.23
Fleet w/ two truck	$15,673.67	$2,978.00	$6,582.94	$1,724.10	$4,388.63

Step 8: Evaluate different fleet combinations by repeating the steps (1-7).

The results obtained in Table 4-9 and Table 4-10 allow the comparison between the analyzed fleet combinations. Nonetheless, it is possible to evaluate a higher number of combinations that may have several factors that differentiate them, rather than only one piece of equipment. Additionally, since the utilization of different equipment may represent a different construction process, it is also possible to compare two environments with significant discrepancies but share one common goal. The ability to compare complex construction environments that differentiate in several factors heavily relies on developing simulation models that effectively represent the real-life process. The following chapter will study a more complex process to demonstrate the application of the proposed framework.

Step 9: Select fleet combination.

For this simplified earthwork process, the fleet combination with two trucks has the lowest operational costs, but it is also the combination that will require the longest time to finish the project. In terms of emissions, when only considering CO, the fleet combination with two trucks produces the highest quantity of pollutants. Thus, it has a higher environmental cost. It is also noticeable that environmental costs have a low impact on the project's overall cost; this is because of the relatively low prices set for the production of pollutants, given in Table 4-6. These prices for the production of pollutants can vary as they are based on judgement. Therefore, it is up to the user to determine whether the environmental cost will significantly impact the total cost of the project and by how much, through conducting simulation experiments as per the proposed method.

In conclusion, if a bigger value is given to the environmental aspects of the project, a construction manager would select to use four trucks. However, if preference is given to the overall cost then a construction manager would consider using two or four trucks as they do not have much difference in costs.

CHAPTER 5: Case Study.

This chapter introduces a case study used to demonstrate the applicability of the proposed framework in evaluating construction processes that may have environmental cost factors. This case study considers an earthwork operation process that is more complex than the one presented in chapter 4, as it takes into consideration uncertainties in construction operations, different equipment in each fleet combination, and changing condition settings. The goal of the case study is to determine which fleet combination will have the greatest financial and environmental value in the project.

5.1 Problem Statement.

An industrial site is undergoing development and requires the formation of a campground. Currently, the proposed campground area is approximately 2,000 meters long and 650 meters wide and has 584,308 bank cubic meters (BCM) of soil that needs to be handled. The general arrangement for the campground is shown in Figure 5-1. The site is designed to have two ponds that will collect drainage water.

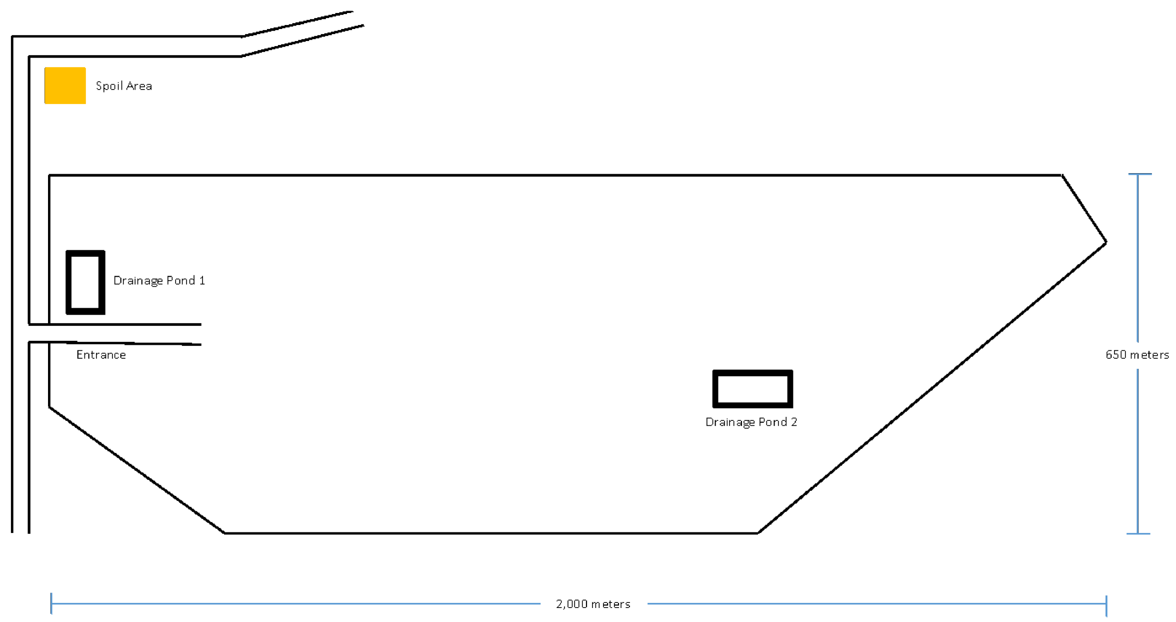

Figure 5-1. Site Layout.

The site was reconstructed into a grid model, as shown in Figure 5-2, to display the localized areas that will require either filing or cutting. There are 48 grids sized at 150 meters by 150 meters, and each grid has an earth volume specified in BCM. Cut volumes are denoted with "-" while fill volumes are denoted in "+." The order at which each area will be develop follows the numbering order shown in Fig 5-2.

Cell 1 -15000	Cell 2 -3700	Cell 3 +3700	Cell 4 +9000	Cell 5 +9000	Cell 6 +8000	Cell 7 -1000	Cell 8 -11200	Cell 9 -2300	Cell 10 -22000	Cell 11 -6900	Cell 12 +11200
Cell 13 -62600	Cell 14 +22500	Cell 15 +23800	Cell 16 +26000	Cell 17 +23000	Cell 18 +22200	Cell 19 +8100	Cell 20 -24800	Cell 21 -9900	Cell 22 -2200	Cell 23 +14300	Cell 24 +7900
Cell 25 -3700	Cell 26 +22500	Cell 27 +28100	Cell 28 +23000	Cell 29 +24300	Cell 30 +14200	Cell 31 -12400	Cell 32 -34400	Cell 33 -72500	Cell 34 -28500	Cell 35 -2500	Cell 36 0
Cell 37 0	Cell 38 -1400	Cell 39 +2300	Cell 40 +1200	Cell 41 +9000	Cell 42 -5900	Cell 43 -9900	Cell 44 -2700	Cell 45 +2300	Cell 46 -100	Cell 47 0	Cell 48 0

Figure 5-2. Design Cut and Fill Volumes Onsite.

The types of equipment involved in the development of the campground are rollers, graders, loaders, trucks and excavators. Following the lean operation component of the established framework, shown in Figure 5-3, the excavator was identified as the critical resource and the varying supporting equipment are the hauling trucks. The respective volume capacities of the equipment and cycle times need to be accounted for in configuring a fleet that will maximize the construction system's efficiency while lowering the total cost of the project. Likewise, the environmental performance of the fleet needs to be considered in the equipment selection.

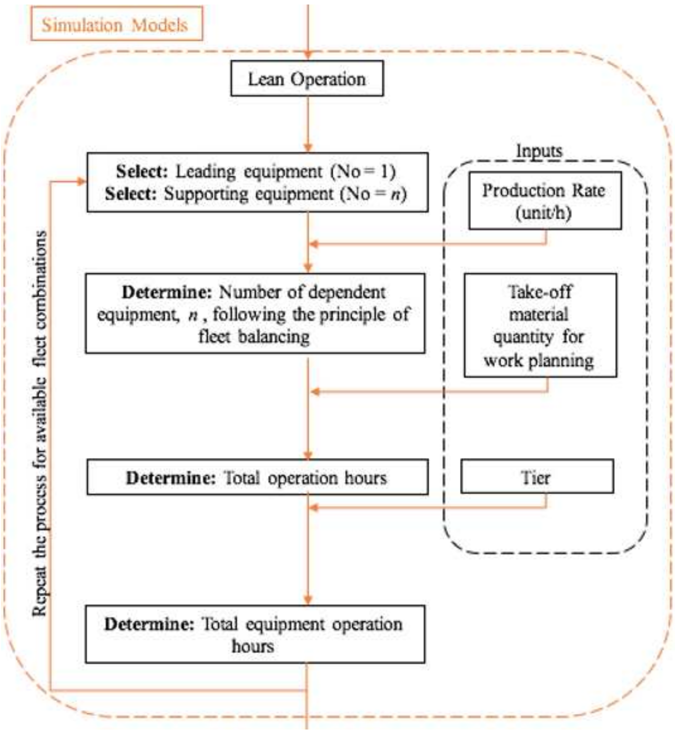

Figure 5-3. Lean Operation Component of Developed Framework.

In order to identify the number of dependent equipment that will allow the excavator to work at its highest productivity, the principles of fleet balancing need to be incorporated into the model. Using the total number of equipment involved in the system, total quantity of material that needs to be handled, and the implementation of a simulation model it is possible to determine the total working hours for each piece of equipment and the total duration of the project.

The fleet responsible to develop the site is composed of one roller, one grader, one loader, one excavator and an unknown number of trucks. During the work planning stages, it was determined that the distinct fleet combinations that are being considered for the project vary in the model of hauling truck to be utilized. Table 5-1 shows the fleet combinations that are considered for the campground site's development.

Table 5-1. Possible Fleet Combination

Fleet Combination	Hauling Truck Type	Excavator Type
1	Caterpillar 730C	Caterpillar 336D
2	Caterpillar 735C	
3	Caterpillar 740C	

The typical cycle of a hauling truck consists of traveling to a specific cut area, where an excavator is removing the soil and a loader will be responsible to load the truck with the removed soul. Once filled, the hauling truck will then travel to a fill area where it will dump its contents and return to being the cycle. When a fill area has been provided with the required soil, a grader and a compactor will then complete then complete the development of the area. The typical cycle is similar to what is shown in Figure 4-2.

In order to determine the number of excavator's loading cycles to fill up a truck load, it is required to consider the ration between bucketload and truckload. A Caterpillar 730C is able to carry 13.3 BCM, a Caterpillar 735C is able to carry 15 BCM, while a Caterpillar 740C is able to carry 18 BCM. A bucketload for a Caterpillar 336D is able to carry 1.8 BCM and takes 0.24 min to complete one cycle, that is load a bucket, swing loaded, dump the bucket, and swing back empty (Caterpillar Handbook, 2017). Regardless of truck type, the truck dumping in fill time is assumed to be a uniform distribution of a high value of 5.5 min and a low value of 4.5 min. It is assumed that a grader and a compactor will require 10 minutes each to grade and compact two full loads from the hauling trucks, and the loader has the same cycle characteristics as Caterpillar 740C. The supporting equipment, with the exception of the hauling trucks, are assumed to have a speed of 30km/hr when relocating from one cell to another.

In order to compare the environmental performance for each fleet combination, it is only required to estimate the amount of emission from the hauling trucks. To do so, the Green Operation component of the established framework, shown in Figure 5-4, needs to be followed. For this case study, the methodology to perform environmental assessment that was established by Lewis (2009) will be used. It is important to note that the collected data that allowed the development of Lewis' equations did not explicitly consider the conditions of the soil and haul roads, thus for the case study such factors are also not considered in simulation modeling and assumed to be the same as in Lewis' study or the normal working conditions. As Lewis' equations to estimate emissions are based on the loads imposed on the engine and the amount of time spent in each engine mode, it is necessary to develop a model that evaluates these parameters. As no data collection was carried out for the assessment of the case study the equations formalized by Lewis (2009), shown in Table 2-10, are used to estimate the emissions from the hauling truck, and thus need to be integrated in the development of a simulation model.

The Green Operation Component of the framework, shown in Figure 5-4 illustrates the decision process to effectively apply Lewis' methodology in estimating emissions. Overall, the use of the framework, shown in Figure 3-1, aims to determine the total duration, operational cost, production of pollutants and the environmental costs associated with each fleet configuration in terms of most likely or averaging values. The statistical analysis of the simulation outputs is not performed due to the lack of input data. It is noteworthy that collecting more data on emission output in particular engine modes and fitting emission models as statistical distributions is out of the scope of this thesis and will be extended in the future research.

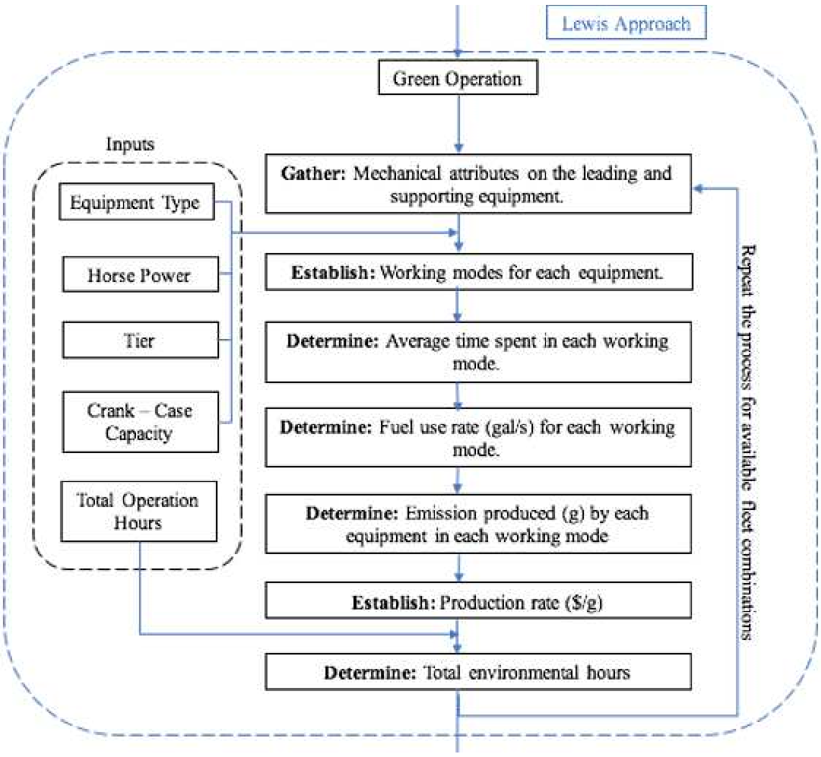

Figure 5-4. Green Operation Component of Developed Framework.

The speeds associated with each engine mode for each type of hauling truck can be seen in Table 5-2. The speed for each hauling truck is assumed to be a triangular distribution, for simulation purposes and the time spent in each working mode is to be approximated with discrete probabilities (similar to emission output models, more data collection and statistical distribution fitting will be recommended in future research to enhance the simulation model's reliability), as shown in in Table 5-2. The mechanical attributes for the hauling trucks were obtained from the Caterpillar Handbook (2007) and are also summarized in Table 5-2. The tier classification for each hauling truck can be found in Table 2-7 and the year model for all trucks is assumed to be 2005. An efficiency factor of 0.75 is assumed for the operating equipment, and the operating rates are shown in Table 5-3.

Table 5-2. Hauling Trucks Reference Speed

Hauling Truck	Engine Mode	Horsepower (hp)	Probability (%)	Loaded Speed (km/hr)			Unloaded Speed (km/hr)		
				Min	Mode	Max	Min	Mode	Max
730C	1	Idle	Idle	0	0	0	0	0	0
	2	42	9	0	6	7	0	8	10
	3	83	17	7	12	14	10	13	17
	4	125	15	14	15	21	17	21	24
	5	167	16	21	22	34	24	29	37
	6	208	13	34	36	40	37	45	45
	7	250	10	40	49	51	45	55	56
	8	292	9	51	55	55	56	58	60
	9	333	8	55	55	60	60	63	65
	10	375	3	60	63	63	65	68	68
735C	1	Idle	Idle	0	0	0	0	0	0
	2	50	9	0	3	4	0	6	7
	3	100	17	4	5	8	7	8	11
	4	151	15	8	10	13	11	12	16
	5	201	16	13	16	20	16	20	23
	6	251	13	20	27	31	23	29	36
	7	301	10	31	31	39	36	42	44
	8	352	9	39	44	50	44	48	55
	9	402	8	50	54	54	55	56	59
	10	452	3	54	59	60	59	64	65
740C	1	Idle	Idle	0	0	0	0	0	0
	2	49	9	0	5	8	0	5	11
	3	98	17	8	8	12	11	12	15
	4	146	15	12	14	21	15	23	24
	5	195	16	21	21	24	24	26	27
	6	244	13	24	28	31	27	27	36
	7	293	10	31	38	40	36	40	45
	8	341	9	40	40	46	45	47	51
	9	390	8	46	52	53	51	56	58
	10	439	3	53	53	58	58	59	63

Table 5-3. Equipment and Operator Rates

Equipment	Equipment Rental Rate (\$/hr)	Operator Rate (\$/hr)
Caterpillar 730C	90	62
Caterpillar 735C	105	62
Caterpillar 740C	120	62
Caterpillar 336D	240	87

A construction manager is tasked to evaluate each fleet configuration in terms of environmental and financial performance. The methodology associated with the established framework is carried out to assess the case study. The application of the framework is demonstrated in the following section.

5.2 Application of Operational Framework.

In order to determine the performance of each fleet configuration, the earthwork processes were analyzed through the application of the proposed framework, presented in Figure 3-1. The framework aims to select the leanest fleet by preventing overproduction caused by unbalanced operating rates between different equipment types and by considering environmental performance as a cost factor.

The framework can also be implemented in the assessment of different construction processes. It uses simulation models and Lewis's environmental assessment for guiding equipment selection and evaluating fleet alternatives. For this specific case, the model shown in Figure 5-5 was developed to perform each fleet's analysis and its impact on operational and environmental costs.

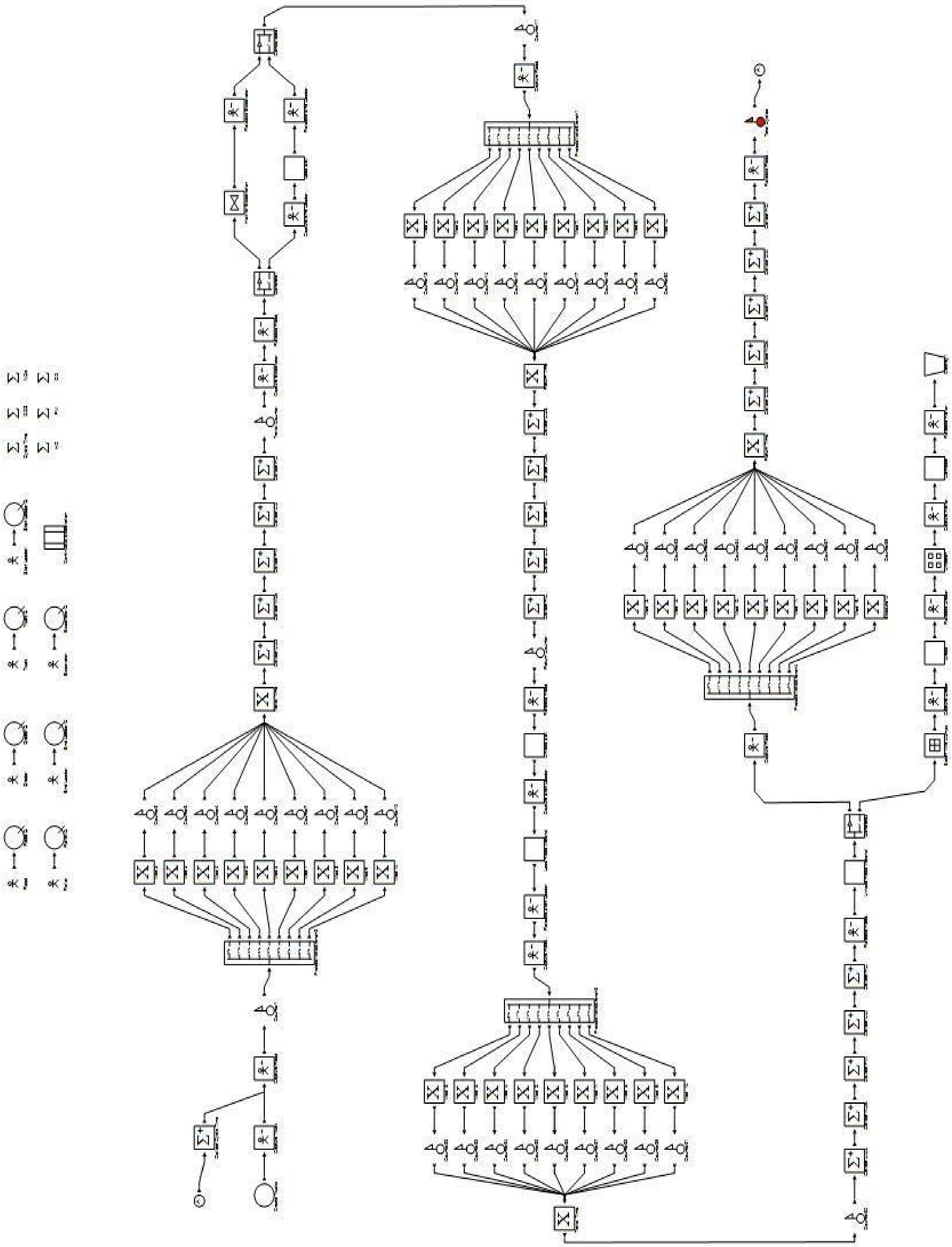

Figure 5-5. Model Developed in SIMPHONY to Analyze the Environmental and Financial Impacts of Utilizing Different Combinations of Hauling Trucks.

The simulation model applies the basic principle of fleet balancing to set the productivity of a piece of equipment (leading resource) as high as practically possible. For this case study, the simulation model considers the Caterpillar 336 D Excavator as the leading resource.

The simulation model created for this case study depicts the interactive process in earthwork construction with trucks, excavators, loaders and graders engaged in a cyclic earthmoving operation. In this simulation model, a cycle begins by hauling trucks travelling to the site where the excavator piles up the cut soil. The speed taken by the hauling truck is determined by the effort created by the engine during travelling (engine mode). Once the truck has arrived, a loader will begin to fill the truck with the excavated soil, while another empty truck begins its journey towards the excavation point. After the hauling truck is fully loaded, it will then travel towards a designed point to dump its content. Once enough soil has accumulated at the designated point, a grader and a roller will be responsible for compacting the area. Once the hauling truck has unloaded, it will then begin another cycle to haul soil.

To evaluate each fleet's performance, the model created in SIMPHONY uses the mechanical attributes for both the leading and supporting equipment. Since the changing equipment of the construction system is the hauling trucks, the duration to complete a cycle mainly depends on the loading capacity, engine power and speed. Additionally, the number of trucks used in each fleet combination varies as each system aims to use the excavator as efficiently possible.

To assess each particular fleet combination's environmental performance, the earthmoving operation simulation modeling approach is developed as guided by the methodology developed by Lewis (2009). This methodology was explained in detail in Chapter 2, and a step-by-step demonstration of its application was given in Chapter 3. It is crucial to note that the lack of data collected in Lewis' work hinders the creation of distributions for emission models. Nevertheless, Lewis was successful in developing an estimating methodology that uses field data and considers mechanical attributes of equipment. Despite the limited data collected, the engine modes classification and the average emission measured under each engine mode provide valuable inputs for the simulation of environmental performance in terms of model and data structure. Overall, the incorporation of fuel use and emission estimates from Lewis in the earthmoving simulation model in instrumental in determining the environmental costs associated with the use of a specific piece of construction equipment that emits large amounts of pollutants.

The use of Lewis' methodology was implemented into the evaluation of the case study as it takes into consideration data that was collected from the field during Lewi's work to develop mathematical equations that relate energy use and emission from construction equipment. Other previously established estimating methods do not consider the impact that varying loads have on the engine's production of pollutants. Additionally, Lewis methodology allows emissions to be considered as a cost factor and performance indicator.

One input factor that Lewi's methodology heavily relies on is the prices given to each type of pollutant production. This is a set price given by the individual decision-maker performing the assessment and has a great influence on the final environmental results derived from this process. The set prices for the emission of each pollutant can be seen in Table 4-6.

It is worth mentioning that the verification of the simulation model created for the evaluation of the case study is performed using the simulation tracing tools provided by SIMPHONY. The software provides the developers and users with trace results, error messages and integrity checks, as well as run-time errors that may be detected in a developer's code. During the development of a model, SIMPHONY allows a user to embed trace messages at key points to verify the execution sequence of the introduced code. Once the model is executed as required, trace messages can then be embedded that allows tracking the occurrences of simulation events in the model to ensure the model reflects correctly what is being evaluated or to get a better understanding of the interaction between the elements and activities that make up the model (Abourizk & Mohamed, 2001).

Through the application of the lean principles set out in the Framework, the simulation model shown in Figure 5-5 is able to determine the number of hauling trucks that will maximize the productivity of the one excavator in each fleet combination. Table 5-4 shows the number of trucks used in each fleet combination. This table reflects how each hauling truck's mechanical attributes can have a significant impact on the productivity of the construction system.

Table 5-4. Results from the application of Lean Operations.

Fleet Combination	No. of Trucks Used	Total Duration (h)
Caterpillar 730C & 336 D Excavator	4	1896.45
Caterpillar 735C & 336 D Excavator	4	1701.77
Caterpillar 740C & 336 D Excavator	4	2166.00

Furthermore, the use of simulation models to evaluate a construction system allows additional aspects of equipment performance to be determined. As exhibited in Table 5-5, the developed model determines the fuel use by the trucks, and its associated costs.

Table 5-5. Truck Results.

Fleet Combination	Truck Fuel Use (gal)	Trucks Fuel Cost ($)	Trucks Use Cost ($)
Caterpillar 730C & 336 D Excavator	30983.65	$66,924.67	$865,655.85
Caterpillar 735C & 336 D Excavator	32819.36	$70,889.81	$786,650.24
Caterpillar 740C & 336 D Excavator	33107.68	$71,512.58	$760,635.87

The table above clearly shows that the fleet combination that will take the longest time to complete the campground development is not necessarily the fleet with the highest truck use costs; however, associated with the highest fuel use cost.

The results in Table 5-6 display the total fuel use and total cost associated with the campground development. These results do not reflect the costs associated with equipment's environmental performance and rely only on the assessment of the proposed framework (the Lean Operations assessment). The results convey that a fleet with 740 C trucks will create the highest fuel costs and use; whereas a fleet with 735 C trucks will make the project costs significantly lower.

Table 5-6. Final Results.

Fleet Combination	Total Fuel Use (gal)	Total Cost
Caterpillar 730C & 336 D Excavator	40246.85	$1,572,728.10
Caterpillar 735C & 336 D Excavator	41131.64	$1,431,972.75
Caterpillar 740C & 336 D Excavator	43687.5	$1,563,282.88

In order to accomplish a comprehensive evaluation of alternative fleets in equipment selection and work planning for the development of the campground, the “Lean” and “Green” operations of the Operational Framework are linked. To do so, a dollar value was assigned to each gram of pollutant emitted, and quantification of emissions was obtained through Lewis’s (2009) methodology.

The developed simulation model determines the environmental cost from a fleet by performing the following steps:

1. Take into consideration the following inputs from the user:

    a. Speed of a truck while travelling, which is a value that is dependent on the engine mode.

    b. Rate of emission in each working mode, which is derived from the methodology proposed by Lewis (2009) and takes into account the mechanical attributes of the equipment, as explained in Chapter 3.

    c. Volume of soil that needs to be hauled.

    d. Productivity of the excavator, which is specified in the task element shown below.

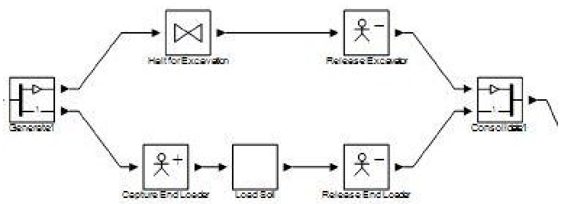

Figure 5-6. Excavator/ Loader Task Element.

In the model created for the assessment of the case study, the inputs that are stochastic are the amount of time spent in each working mode for every activity, and speed of trucks as it is dependent on the effort created by the engine. The reason for these inputs to be stochastic is due to the constant changes in engine effort that a hauling truck experiences when performing some type of work. Trucks needs to constantly speed up, reduce speed and make quick tops to complete a task. This is also similar to the duration that an excavator requires to excavate soil and fill a truck. On the other hand, the rate of emission at each working mode is a constant value due to the lack of extensive data. Lewi's work gathered enough field measurements to determine emission rates for a range of normalized MAP values. Thus, using constant values for a changing variable, such as emission rates, is due the lack of more data to fit into input distribution. It is important to not that the lack of more extensive data is cause by the high costs associated with the execution of suck projects.

2. Allow the model, shown in Figure 5-5, to run and make the following process.

    a. A truck leaves the point of origin and travels toward a grid, during this travel an engine mode is assigned to the truck which is then used by the model to calculate its travel time. This is done through the Execute Elements shown in Figure 5-7 and user-written code shown in Figure 5-8.

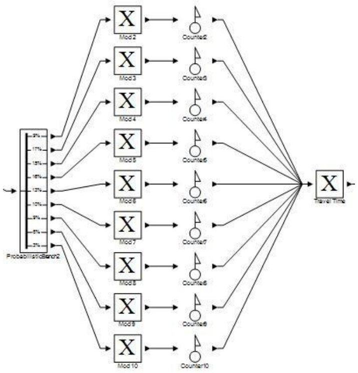

Figure 5-7. Execute Elements to Assign Engine Modes.

```
Public Partial Class Formulas
    Public Shared Function Formula(ByVal Element As Simphony.General.Execute) As System.Boolean
            Select Case LX(1)

                Case Is = 2 'Mod 2
                Dim Duration = (40 + Count("End Counter")) / SampleBeta(5.2,3.7,1.5,2.8)
                ScheduleEvent(Element.OutputPoint, Duration)

                Case Is = 3 'Mod 3
                Dim Duration = (40 + Count("End Counter")) / SampleBeta(5.9,4.3,0.6,1.1)
                ScheduleEvent(Element.OutputPoint, Duration)

                Case Is = 4 'Mod 4
                Dim Duration = (40 + Count("End Counter")) / SampleBeta(5.2,3.7,1.5,2.8)
                ScheduleEvent(Element.OutputPoint, Duration)

                Case Is = 5 'Mod 5
                Dim Duration = (40 + Count("End Counter")) / SampleBeta(5.2,3.7,1.5,2.8)
                ScheduleEvent(Element.OutputPoint, Duration)

                Case Is = 6 'Mod 6
                Dim Duration = (40 + Count("End Counter")) / SampleBeta(5.9,4.3,0.6,1.1)
                ScheduleEvent(Element.OutputPoint, Duration)

                Case Is = 7 'Mod 7
                Dim Duration = (40 + Count("End Counter")) / SampleBeta(5.2,3.7,1.5,2.8)
                ScheduleEvent(Element.OutputPoint, Duration)

                Case Is = 8 'Mod 8
                Dim Duration = (40 + Count("End Counter")) / SampleBeta(5.2,3.7,1.5,2.8)
                ScheduleEvent(Element.OutputPoint, Duration)

                Case Is = 9 'Mod 9
                Dim Duration = GX(1) / SampleBeta(5.9,4.3,0.6,1.1)
                ScheduleEvent(Element.OutputPoint, Duration)

                Case Is = 10 'Mod 10
                Dim Duration = (40 + Count("End Counter")) / SampleBeta(5.2,3.7,1.5,2.8)
                ScheduleEvent(Element.OutputPoint, Duration)

            End Select

        Return False

    End Function
End Class
```

Figure 5-8. Sample User-Written Code in Execute Elements.

b. As the truck is traveling, the model begins to measure the emissions produced by the truck through the Collect Statistic Elements shown below.

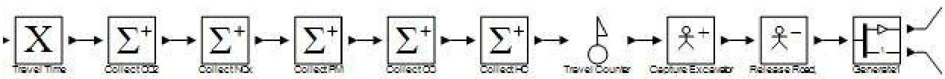

Figure 5-9. Collect Statistic Elements to Measure Emission Produced by Trucks.

c. Once the truck arrives at the assigned grid, a loader / excavator will fill up the hauling bed. While this happens, the truck will idle and produce pollutants that are measured through the emissions configurations settings provided by SIMPHONY, as demonstrated in the figure below.

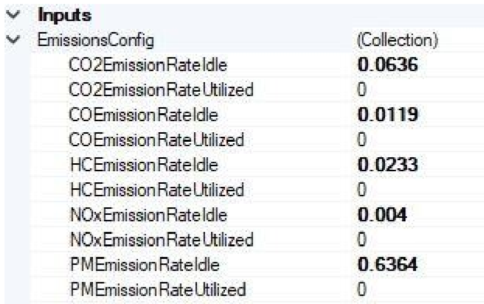

Figure 5-10. Emission Configuration Setting Assigned to Trucks.

d. Once the truck is full, it then travels to the assigned grid where it should dump the soil. The emissions taken during the travel time and dump time are evaluated as done in point a - c.

e. Once the truck has dumped the soil, it will then travel to its point of origin and begin a new cycle.

f. When the model achieves simulating the hauling of the total volume of soil specified, it will stop running.

3. Gather results from the simulation.

a. The main set of results that need to be obtained from the simulation model are the total project duration, % of time spent in each activity mode, and the total amount of pollutants produced in each activity. Table 5-7 shows a sample table that reflects the outputs that can be derived from the analysis of a simulation model developed in SIMPHONY.

Table 5-7. Sample Results Obtained Through SIMPHONY

Non-Intrinsic Statistics

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Scenario1 (Termination Time)	5,664.062	0.000	1.000	5,664.062	5,664.062
CO	5.001	12.245	403.000	0.000	79.528
CO2	18.325	42.176	403.000	0.000	256.749
Cycle Time	2,706.322	1,580.006	99.000	248.739	5,624.062
Halt for Excavation (Valve Changes)	1.000	0.000	1.000	1.000	1.000
Halt for Excavation (Valve Closes)	0.000	0.000	1.000	0.000	0.000
Halt for Excavation (Valve Opens)	1.000	0.000	1.000	1.000	1.000
HC	13.681	34.409	403.000	0.000	214.985
NOx	2.770	14.850	403.000	0.000	171.988
PM	175.110	399.588	403.000	0.000	2,374.516

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
End Loader (Inner Resource)	18.0%	38.4%	100.0%	0.0%	1.000
Excavator (Inner Resource)	3.2%	17.7%	100.0%	0.0%	1.000
Grader (Inner Resource)	8.8%	28.4%	100.0%	0.0%	1.000
Road (Inner Resource)	95.4%	21.0%	100.0%	100.0%	1.000
Roller (Inner Resource)	17.7%	38.1%	100.0%	0.0%	1.000
Start Loader (Inner Resource)	18.0%	38.4%	100.0%	0.0%	1.000
Truck (Inner Resource)	100.0%	0.0%	100.0%	100.0%	4.000

By considering a rate cost for each pollutant's production, as seen in Table 4-6, and total amount of emission produced, it is possible to assess the analyzed fleet configuration's environmental cost. The case study's environmental results can be seen in Table 5-8, Table 5-9 and Table 5-10. It is crucial to highlight that the environmental results, obtained in this case study, are based on average number of simulations and the average performance data obtained by Lewis (2009).

Table 5-8. Quantity of Emissions Produced.

Fleet Combination	NO_x Produced (g)	HC Produced (g)	CO Produced (g)	CO_2 Produced (g)	PM Produced (g)
Caterpillar 730C & 336 D Excavator	4600673.20	463607.79	1196682.25	401602.81	38234.57
Caterpillar 735C & 336 D Excavator	5174956.69	519670.4	1343959.35	452835.96	43144.53
Caterpillar 740C & 336 D Excavator	5349911.44	536747.17	1388836.78	468442.83	44640.15

Table 5-9. Cost Resulted from Each Type of Emission.

Fleet Combination	NO_x Cost	HC Cost	CO Cost	CO_2 Cost	PM Cost
Caterpillar 730C & 336 D Excavator	$28,005.66	$2,445.84	$9,712.75	$16,297.84	$465.49
Caterpillar 735C & 336 D Excavator	$31,501.50	$2,741.60	$10,908.11	$18,376.98	$525.27
Caterpillar 740C & 336 D Excavator	$32,566.50	$2,831.69	$11,272.35	$19,010.34	$543.48

Table 5-10. Final Environmental Results.

Fleet Combination	Total Environmental Cost
Caterpillar 730C & 336 D Excavator	$56,927.57
Caterpillar 735C & 336 D Excavator	$64,053.45
Caterpillar 740C & 336 D Excavator	$66,224.35

The above results reflect that production of each pollutant varies significantly. While Nitric Oxide (NOx) is the highest pollutant produced, Particulate Matter (PM) is produced significantly less. The production of each pollutant is a function of the consumption of fuel performed by each construction equipment, thus due to the similar mechanical attributes of each hauling truck, the total production of each pollutant is comparable among them, as exhibited in Table 5-8.

The overall costs, including environmental costs associated with each fleet combination, are displayed in Table 5-11. This table shows that the fleet with 740 C trucks produced the most significant amount of pollutants, while the fleet with 730 C trucks produced the least. When considering the results demonstrated in Table 5-9, the highest and lowest environmental costs are associated with the 740 C truck fleet and the 730 C trucks fleet, respectively.

Table 5-11. Case Study Results.

Fleet Combination	Overall Cost
Caterpillar 730C & 336 D Excavator	$1,629,655.67
Caterpillar 735C & 336 D Excavator	$1,496,026.20
Caterpillar 740C & 336 D Excavator	$1,629,507.23

The results from the case study exhibit the high impact that environmental costs can have on selecting equipment. Although the fleet combination that uses 730 C trucks represents the fleet with the highest overall cost, it is not the option with the lowest duration. Hence, if a higher priority is given to the project's duration, a project manager will be encouraged to select a fleet with 735 C trucks. In the case where the environmental aspect of the project is given a higher priority, then a fleet combination with 730 C trucks will be selected. These results show how each fleet combination will provide some type of benefit in terms of duration, costs and environmental impact. Additionally, it demonstrates that quantification of house emissions as a cost factor can become a performance indicator in unit cost ($/g).

5.3 Analysis and Suggestions.

The framework aims to select a fleet configuration that will maximize the efficiency of a construction system and mitigate the production of greenhouse gases. To accomplish so, the framework relies on the assessments performed by simulation models and environmental assessment tools. For the case study, a simulation model created in SIMPHONY was utilized as well as the environmental assessment tool developed by Lewis (2009).

The framework uses simulation models' assessment capacities to accomplish 'lean operations' in a construction system. The model evaluated equipment's involvement over time, where field conditions may change at a certain point in time or as causes of specific circumstances. Additionally, the construction process simulation represented an efficient method to identify bottlenecks and consider options to improve the productivity of the system while eliminating the need to consume time and resources. Overall, the application of simulation models to analyze construction processes is practical in assessing complex relationships between leading and supporting equipment by incorporating engineering principles.

Another aspect of the framework demonstrated in the case study is the incorporation of 'Green' operations into the assessment of construction processes. In this study, Lewis's work to measure greenhouse gas emissions from construction equipment was used, so these emissions can be quantified as a cost factor. By doing so, it was determined that a fleet combination that takes the shortest amount of time to complete a project does not necessarily represent the most environmentally efficient option, nor the least expensive. Therefore, the quantification of greenhouse gas emissions as a cost factor can be used as a performance indicator to analyze construction operations.

Lewis's work exemplifies how the construction industry needs tools to quantify their impact on natural resources effectively (Lewis, 2009). Simultaneously, there are so many methods, materials and resources used in different construction projects that it is a great challenge to assess every environmental impact produced by each agent. Nevertheless, with the development of technology, the construction industry has achieved significant progress.

Another critical aspect demonstrated through the case study is that research on equipment selection and simulation of construction processes have been predominantly productivity-driven, mainly focusing on increasing equipment utilization efficiency so a project can be delivered on time and under budget. However, one major limitation of productivity-driven research is that the environmental aspect of construction is mostly neglected. The Framework successfully established a methodology based on the use of simulation models and environmental tools that create a lean construction system that considers environmental impacts.

Chapter 6: Conclusion.

This chapter presents the finding and limitations that resulted from this work. The conclusions are categorized by a general overview of the proposed framework's applicability to integrate simulation and emission models, and its contribution to the construction industry. Also, the limitations found in the development of this work are listed. This chapter concludes by outlining the future study that can be performed in the matter of making the construction industry more ‘lean’ and ‘green.’

6.1 General Findings.

As the construction industry is considered among the largest consumers of natural resources and main producer of greenhouse gases, there has been a growing concern over the negative impact that this industry has on the environment (Černoch, 2017). In particular, the industry lacks strategies to reduce the large amount of pollution created by the use of heavy equipment. The work performed in this research establishes a framework that integrates simulation and emission models that guide in the selection and use of heavy equipment. The use of the framework allows construction systems to become lean (cost-effective) and green (environmentally conscious and sustainable).

This results from this study support the work of Chien, Gao, and Meegoda (2013) in encouraging the development of models that can contribute to the analysis of construction operations. Additionally, the work of Bayzid (2014) is also supported by the proposed Framework as it demonstrates that proper management of fleet configuration can positively impact the cost of a project.

A study that proposes a direct mechanism to quantify emissions from construction equipment is rare to find, especially one that is performance analysis based on field measurement data such as Lewis’ work. The implementation of Lewis’s methodology into the proposed framework demonstrated its applicability to quantifying greenhouse gases, at the same time, it established that using greenhouse gas emissions as a cost factor can be used as a performance indicator of heavy equipment.

This research also supports the work performed by Sadha (2012) *Modeling Reclamation Earthwork Operations Using Special Purpose Simulation Tool* on the applicability of SIMPHONY to evaluate complex earthwork operations. Through the simulation of construction operations, it is possible to assess the impact that varying conditions may have on the completion of a project and determine engineering solutions that will increase the efficiency in the work procedures of a project.

The academic contribution of this work is that the integration of simulation models with environmental assessments advances the applicability of simulation models to evaluate earthmoving operation in a more detailed, analytical manner. Additionally, the established framework aids the development of environmental assessment models based on dynamic system simulation through generalizing the structure of the simulation model, defining model parameters and logical relationships between them. On the other hand, the developed framework clearly defines the required information and system logic that will assist members of the construction industry in performing analysis of construction systems through the application of dynamic and interactive simulation and environmental impact assessment.

6.2 Limitations.

The conducted research contained the following limitations:

- Validity of the research depends on Lewi's data. No field data was collected for the analysis of the case study; instead, field measurements from Lewis' work were used to develop a link between equipment attributes and pollutants' production. Nevertheless, Lewis performed extensive data evaluation to eliminate any values that would produce invalid results.

- The final results obtained in the case study are based on averages from multiple simulations and Lewis' field measurements; therefore, they are still deterministic. With the advancements of technology, field data gathering performed by Lewis will not be too expensive to scale up enabling a more in depth and accurate statistical analysis in line with simulation modeling.

- Accuracy on fleet evaluation heavily depends on the complexity and completeness of a simulation model. Nevertheless, the developed model for the case study provides transparency to confirm the applicability in studying equipment combination as per the proposed framework.

- The cost values given to the production of each pollutant is based on judgement. These values can significantly impact the overall environmental cost; thus, it is critical to use rational values.

As a result, the contribution of this work lies in the integrated model framework being proposed, the structure of the problem, and the parameters identified along with interred relationships. Similarly, the framework provides a cost-effective and environmentally conscious methodology to assess heavy equipment utilization and provide a higher efficiency construction system that contributes to more environmentally sustainable operations.

6.3 Future Study.

Besides the accomplishment obtained through this work, aspects of this study identified areas that need further study. An example of these areas is the monetization of environmental impacts. Although private organizations and governments have been working to create cost rates associated with contamination of the environment, there is still a need for an adequate method to set an economic value on human activity's environmental impact. The method to set a monetary value to the environmental impacts also needs to consider the social and financial implications. Determining an accurate financial cost on environmental impacts represents extensive work and a future achievement towards a sustainable society.

Similarly, another obstacle related to the monetization of environmental impacts in the construction industry in the high costs associated with gathering vast and valid field data on emissions. Studies that aim to reduce the cost in assessing the environmental performance of machinery will be a great contribution to develop stochastic simulation analysis that are backed up with significant field data.

Another area that requires further work is the study of environmental impacts created by each construction equipment. Through the work of Lewis (2009), a methodology was created to evaluate fuel use and emissions rates among various construction equipment, but this equipment only represents a small percentage of machinery used in the industry. Therefore, further developing the link between equipment use and greenhouse emissions by obtaining field data from a larger number of equipment will provide a more accurate assessment of greenhouse emissions.

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Appendix: SIMPHONY - User Manual

1. What is SIMPHONY?

Simphony created in 1998 by Dr. Simaan AbouRizk, and Dr. Danny Hajjar is a simulation system that has continued to evolve with the past of the years and is currently being extended and maintained by AbouRizk's research team at the University of Alberta (ABouRizk et al., 2016). Hajjar and AbouRizk (1999) defined SIMPHONY as "a Microsoft Windows-based computer system developed with the objective of providing a standard, consistent and intelligent environment for both the development as well as the utilization of construction tools. (p. 999)" Indeed, SIMPHONY offers a model environment that is composed of simulation services and a modelling user interface.

1.2 Features

SIMPHONY as a tool developer allows professionals to implement highly flexible simulation tools that "support graphical, hierarchical, modular and integrated modeling with great ease" (AbouRizk et al., 2016). This simulation model provides adaptables, user friendly environment for the simulation modeling process including support for: (Hajjar and AbouRizk, 1999)

1. Modular and Hierarchical Modeling for the representation of complex and large construction projects.

2. General Purpose Modeling Vs. Special Purpose Simulation (SPS), SIMPHONY supported both modelling constructs (eg. process interaction and CYCLONE) as well as specialized templates for specific construction methods (eg. earth-moving and aggregate production).

3. Integration of SPS Tools, through the construction of models based on several templates (eg. a model based on an earthmoving template as well as a CYCLONE template).

4. Custom Output Results in the form of tables and graphs.

5. Automated generation of externally accessible project planning data in a standard format.

6. Script based modeling for accommodation of advanced users wishing to bypass the graphical user interface.

7. Storage and retrieval of commonly used simulation model structures in the User Model Library

These basic features consist of a comprehensive and complete model definition, compilation and testing platform. AbouRizk and Mohamed (2001) suggest, “Any simulation model built in SIMPHONY is composed of a number of instances of modeling elements that the user creates on-screen and links together with relationships. (p. 1907)” Every single modeling element has its own behavior and performs differently to each event. A group of these modeling elements designed to work together in the same project construction model is referred to as templates.

Templates can be developed in SIMPHONY into two phases: design and implementation phase. For example, the design phase is vital for the choosing of elements and the different behaviours of each element. On the other hand, implementation phase, by AbouRizk and Mohamed (2001) state, “involves the creation of new modeling elements in SIMPHONY using the Template Manager and the customization of the behaviors for each of these elements. The different behaviors of an element are produced by writing code in the form of event handlers that respond to the various events. (p.1908)”

AbouRizk and Mohamed (2001) in *SIMPHONY - An integrated Environment for Construction Simulation* demonstrated the different element behaviors that the developer can customize with a brief description for each.

Table A-1. List of SIMPHONY Services and their Function.

Behavior	Description
Geometric Attributes	Geometric attributes are mainly used for model layout purposes. They define the two dimensional position of the modeling element in relation to other elements. This information is typically used simply for graphical representation purposes.
User Attributes	User attributes include parameters and outputs. Parameters are what engineers will be manipulating to change the properties of the modeling element. Outputs provide exposed features of the modeling element either for the engineer to examine (Performance Indicators), or to be used as inputs to other element parameters.
Relationships	Relationships between modeling elements are used to define the logic of the simulation model and flow path of entities.
Hierarchy	The concept of a hierarchy is supported mainly through the ability of any element to access its parentís as well as its childrenís properties.
Simulation	Simulation behavior defines the resources, files, events and entities of a given element and how each simulation event is handled.
Statistics	Statistical collection is defined at the modeling element level. Examples of statistics are resource utilization, queue lengths, and cycle times.
Planning	The planning behavior defines how a given modeling element transforms its simulation results into a project plan that includes a schedule, production and revenue forecast, resource utilization and costs.
Graphical User Interface	This behavior includes graphical representation, which determines what the modeling element looks like to the engineer. The other aspect of this behavior is graphical manipulation, which defines how an engineer can manipulate geometrical attribute, user attribute, and relationship information.
Animation	This behavior defines the elementís role in the animation scenario if one is produced after simulation.

Note. Reprinted from "*Simphony - An integrated Environment for Construction Simulation"* by AbouRizk, S.; Mohamed. Y. (2001) ResearchGate, p. 1908.

These elements help to build and customize the simulation model in order to create a flexible and detailed user friendly, and easy to use template.

1.3 System Requirements

To get started with SIMPHONY there are certain system requirements to follow before to proceed with the installation:

Table A-2. Installation Requirements.

- Microsoft Windows XP, Windows & (x86 or x64, Windows 8 (x86 or x64)
- 1.6 GHz or faster processor
- 1 GB of RAM (1.5 GB if running on a virtual machine)
- 50 MB of available hard disk space.
- DirectX 9-capable video card that runs at 1024x768 or higher display resolution.

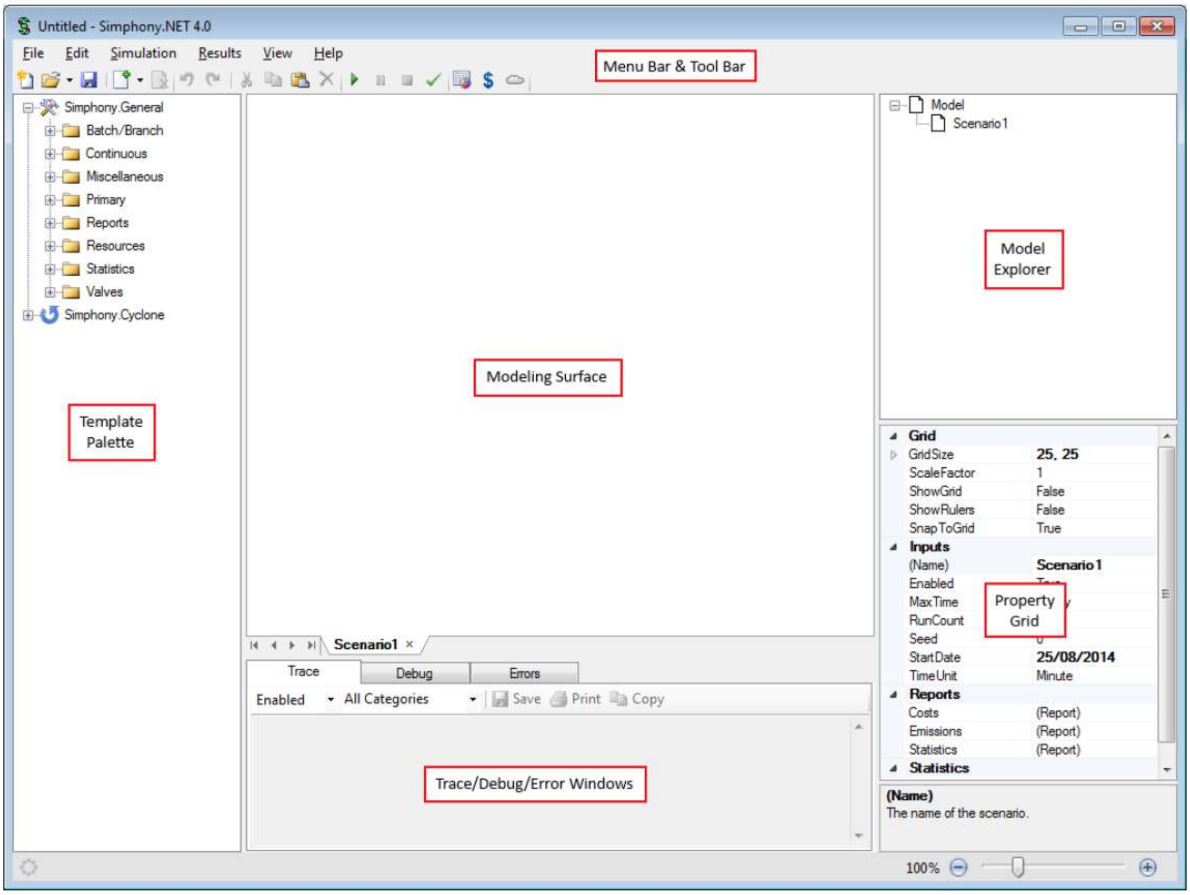
ABouRizk et al., (2016) Construction Simulation: An Introduction to Simphony. University of Alberta, p. 279.

Having the system requirements will allow users to install SIMPHONY.Net program smoothly.

1.4. User Interface.

As mentioned before, SIMPHONY is a "Microsoft Windows-based computer system developed with the objective of providing a standard, consistent and intelligent environment for both the development as well as the utilization of construction tools. (p. 999.)" (Hajjar and AbouRizk, 1999). The primary benefit of SIMPHONY is that it offers a simple, user-friendly interface that simulates a drawing board (Haring, 2014).

Figure A-1. SIMPHONY Modelling - User Interface.



Note. Reprinted from "*Construction Simulation: An Introduction Using SIMPHONY*" by AbouRizk, S; Hague, S; Ekyalimpa, R. (2016) University of Alberta, p. 208.

Figure A-1 shows a screenshot of the SIMPHONY modelling environment. This section is divided into six categories following ABouRizk et al., (2016) Simulation Models description:

1. Menu Bar & Toolbar: Both are located on the top left side of the screen. Menu Bar displays the available menus and commands. It is divided into six categories: *File, Edit, Simulation, Results, View and Help*. Nevertheless, Toolbar contains buttons for frequently used commands: copy, paste, save, delete and others.

2. Template Palette: located on the left side of the screen. It displays a list of all elements available in the modelling element library, constructing new projects. In this section, users can create unique templates by clicking under *File*, the *Add Template* item.

3. Modelling Surface: it is characterized to be a white square located in the middle of the screen. It is the main workstation dedicated to building simulation models. This section allows users to drag and drop modelling elements from the Template Palette and connect them by clicking and dragging between output/input reports. The elements of the Modelling Surface can be controlled by using the sidebar located at the bottom-right corner called Property Grid.

4. Property Grid: placed at the bottom right corner of the screen. It displays the properties of the modelling elements selected on the Modelling Surface. For example, in this section, users can change the name and parameter of modelling elements, specify run times, and run counts. Hence, Property Grid allows users to add and modify elements in the model. As demonstrated in the table below, it is divided in three main sections (ABouRizk et al., 2016):

Table A-3. Property Grid Description.

Grid	
GridSize	A pair of numbers indicating the horizontal/vertical distance between grid lines.
ShowGrid	A boolean value indicating whether or not the grid should be displayed on the Modelling Surface.
SnapToGrid	A boolean value indicating whether or not modelling elements should snap to the grid when they are placed/moved on the Modelling Surface.
ShowRulers	A boolean value indicating whether or not the rulers should be displayed on the Modelling Surface.
Inputs	
(Name)	The name of the scenario.
Enable	A boolean value indicating whether or not the scenario should be simulated when the model is executed.

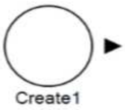
MaxTime	The maximum permissible simulation time: once this time is reached a run will be terminated.
RunCount	The number of times the Scenario should be executed.
Seed	The value for the pseudo-random number generator.
StartDate	The date at which simulation will begin: simulation time zero will correspond to midnight on this date.
TimeUnit	The time unit one unit of simulation time corresponds to.
Reports	
Cost	Provides access to the cost report.
Emissions	Provides access to the emissions report.
Statistics	Provides access to the statistics reports.

Note. Reprinted from "*Construction Simulation: An Introduction Using SIMPHONY*" by AbouRizk, S; Hague, S; Ekyalimpa, R. (2016) University of Alberta, p. 208..

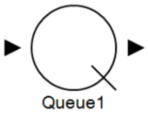
5. Model Explorer: located at the top right corner of the screen. It displays a navigation tree representing the structure of the current simulation project. Under the main model, one or more scenarios can be developed. Hence, each scenario contains slightly different versions of the same simulation model compared after the simulation has been run.
6. Trace/Debug/Error Windows: can be seen at the bottom of the screen. This window communicates logical errors or warnings within the simulation model to the user. Each error/warning message does not allow the model not to run, displaying a message given information about the issue to help the user solve the problem.

1.5. Task Elements.

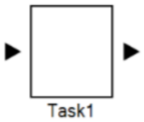
As mentioned in Chapter 4, SIMPHONY used different modelling elements or task elements to represent a different activity in the project. Modelling elements or task elements are the building blocks of the model.



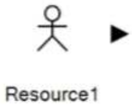
Create Element: Used to create a number of entities at start of simulation or at random intervals during a simulation.



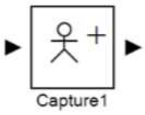
Queue Element: Used as a location for entities to wait until requested resources become available.



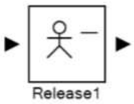
Task Element: Used to hold an entity for a period of time to properly model an activity. A task element may be associated with a specific resource and queue file. In occasions where a resource is not available, entities are forced to wait in the associated queue file.



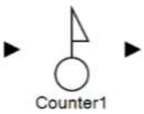
Resource Element: Used to model assets that are required to complete specific tasks elements.



Capture Element: Used to grant the employment of one or more resources by an entity. In the circumstances when the requested resource is unavailable, the entity will be queued in the file element associated with the resource.

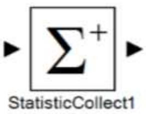


Release Element: Used to allow a capture resource to return to its associate server, once the entity passes through this element.

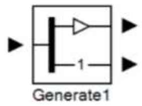


Counter Element: Used to record the number of entities passing through this element and its mostly used to record productivity of a model.

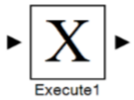
Statistic Element: Used to record statistics associated with the Collect Statistic element.



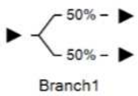
Collect Statistic Element: Used to acquire information every time an entity passes through this element, and it stores it in the Statistic element.



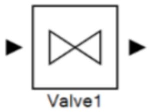
Generate Element: Used to create one or more clones of every entity that passes through this element.



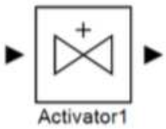
Execute Element: This element runs user written code whenever an entity goes through the element.



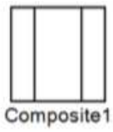
Probabilistic Branch Element: Used to model uncertainty associated with destination of entities going through the branch.



Valve Element: Used to either allow or prevent resources from passing depending on its state: Closed or Open. The state of the valve element is changed through an activator element.



Activator Element: Used to change the state of a valve element once an entity passes through it.



Composite Element: Used to contain an additional simulation model within the primary model that allows users to develop better coordinated simulations.