University of Alberta

The Application of Simulation Methodologies on Estimating Gas Emissions from Construction Equipment

by

Wenjia Pan

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Construction Engineering and Management

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

This thesis is dedicated to my parents, Guoxing and Xuefen, for their

encouragement and continued support

throughout my entire education;

and

to my girlfriend, Huiyi, for her love and "ZiLuTou-special" smoothies

during my graduate degree.

Abstract

Construction contributes significantly to gas emissions. Diverse efforts have been undertaken to mitigate the effects of these emissions; however, there currently is no effective tool to estimate small-scale (e.g., project-based) emissions in construction. Discrete-event simulation (DES), a new approach, may be able to rectify this lack. This research has built a DES-based emission template using Simphony, a special purpose simulation (SPS) environment developed at the University of Alberta. This template permits inexperienced simulators to build simulation models that can estimate emissions of a construction project. Two case studies are used to showcase the modeling process and to demonstrate how valuable information concerning sustainability can be obtained through this method. In addition, this research introduces an emission federate in a high-level architecture (HLA) simulation environment that can estimate emissions without building models; it relies instead upon information provided by other federates (e.g., operation federate), which has been underdeveloped thus far.

Acknowledgements

I would like to thank my co-advisors, Dr. SangHyun Lee and Dr. Simaan AbouRizk, for their direction and support throughout this research. In addition, I really appreciate Dr. Simaan AbrouRizk, Dr. SangHyun Lee and Dr.Michael Lipsett for spending your holiday time on attending my MSc exam and giving important suggestions on my thesis (Dec 24th).

I would also like to thank all members of the Hole School of Construction Engineering for their support and assistance during my graduate program. I would like to thank especially Dr. Mohamed Al-Hussein, whose encouragement was instrumental in commencing this research project; Dr. Yasser Mohamed, whose knowledge and guidance helped me to solve technical problems concerning programming; and my colleagues Mahdi, Mehrdad, Changbum, Meimanat, Hua, Di, Amin, Reza, etc.—their encouragement and support have been really important to me and my research.

As well, many thanks to my parents, Guoxing and Xuefen, whose love always has motivated me to be strong and mature, and to my girlfriend, Huiyi, whose companionship and support has made me happy throughout my studies abroad.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Background

Construction activities use considerable energy and contribute significantly to gas emissions. In 2002, the United States construction sector accounted for 2.6-3% of total U.S. energy consumption (Sharrad et al. 2007). In the same year, United States Environmental Protection Agency (EPA) statistics ranked construction third for the production of greenhouse gas (GHG) emissions among key industrial sectors—the construction industry produced 1.7% of total U.S. GHG emissions (EPA 2009a).

Within construction, equipment (which is mostly diesel-powered) is the primary contributor of emissions: the EPA model states that 32% of all land-based nitrogen oxides (NOx) and 37% of all land-based particulate matter (PM) in the United States in 2005 was produced by construction and mining equipment (US EPA CAAAC 2006). Unfortunately, the volume of these emissions continues to increase. The EPA model (EPA non-road model 2005) estimates that construction and mining equipment emissions soon will account for more than 45% of both NOx and PM produced by non-road (be synonymous with the term "off-road", means engines running on non-public roads) diesel equipment.

Basically, there are two main categories for gas emissions: GHGs and CAPs/CACs. GHGs capture and release heat. They include carbon dioxide (CO_2), methane (CH4), water vapor (H_2O), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbons (CFCs). A high volume of GHGs is a factor in global warming. Criteria Air Pollutants (CAPs), which are classified in Canada as Criteria Air Contaminants (CACs), include sulfur dioxide (SOx), nitrogen oxide (NOx), carbon monoxide (CO), ozone (O_3), particulate matter (PM), and lead (Pb). The primary construction-related gases are CO_2, NOx, CO, PM, and hydrocarbon (HC). HC is included because it is a key component in the formation of GHGs. These five gases negatively affect human life when they are too concentrated. Table 1 displays the major adverse impact of each air pollutant.

The need to reduce construction sector emissions has become more and more evident. Efforts to mitigate construction emissions have included regulations (e.g., technological engine standards) and financial incentives (e.g., carbon taxes). These have required the construction industry to quantify and reduce the effects of emissions. Several generalized methods to estimate emissions, such as the EPA's non-road model (EPA 2005) and the California Air Resources Board's off-road model (CARB 2009), presently exist. A review of the relevant literature in

the following section describes some widely-used methods and analyzes both

their strengths and their weaknesses.

Table 1: Brief negative effects of air pollutants

Gases	Impacts
CO_2	A major element of GHGs ; global warming
CO	Toxic gas; can form smog or ground level ozone; causes respiratory problems; easily forms CO_2 when used
NOx	Can form photochemical smog, ozone, and acid rain; harmful to lung functioning; causes respiratory problems
HC	Can form ozone, which makes the body more vulnerable to infection
PM	Aggravates asthma and other respiratory problems, such as coughing; PM2.5[1] increases the number of deaths due to cardiovascular and respiratory diseases and lung cancer; PM10[2] also affects respiratory morbidity (WHO 2005)

Note:
1. PM2.5 represents particles less than 2.5 micrometers in aerodynamic diameter
2. PM10 is used to describe particles of 10 micrometers or less.

1.2 Literature review

Through the study of current efforts to quantify emissions, a literature review can

be used to define research objectives and provide references. The following

literature review discusses the EPA's non-road model (EPA 2005), the California

off-road model (CARB 2009), Emfac 2007 (CARB 2006), the road construction

emission model (SMAQMD 2009b), the life-cycle assessment method (ISO 1997)

and Lewis' algorism on calculating emission factors (Lewis, 2009).

1.2.1 EPA non-road model

The NON-ROAD 2005 model designed by the EPA estimates CO_2, CO, NOx, PM, HC, and SOx emissions produced from non-road sources in the U.S. It is considered an authoritative model for emission estimation. Figure 1 shows the operational interface for this model.
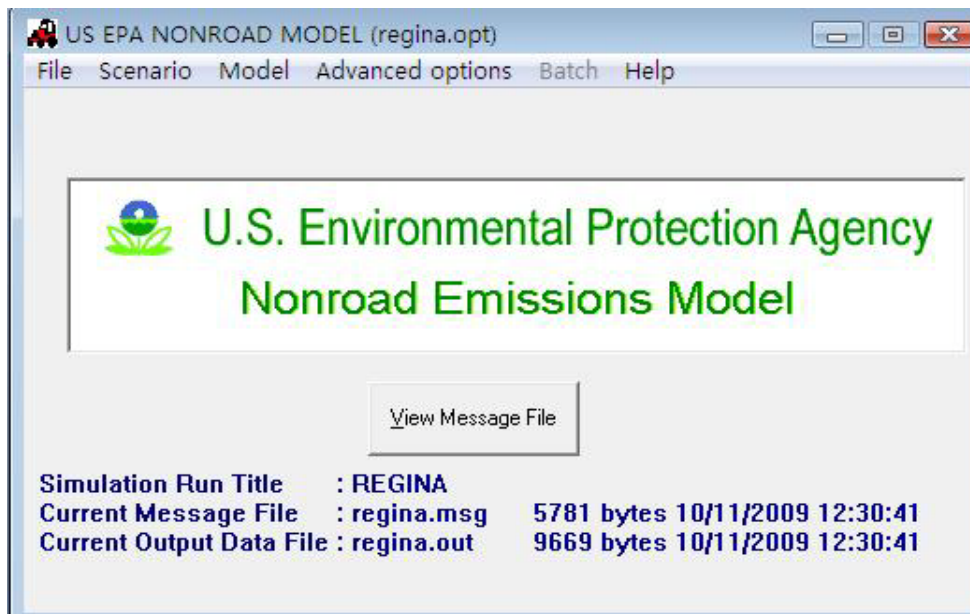
Figure 1: The operational interface for the EPA's NON-ROAD 2005 model (EPA 2005)

The features of this model are (EPA 2005):

1) The model includes more than 80 basic and 260 specific types of non-road equipment. Further, it stratifies equipment type through the rating of horsepower. All referred equipment is produced no earlier than 1996. Equipment fuel types include gasoline, diesel, compressed natural gas (CNG), and liquefied petroleum gas (LPG).

2) The geographic area(s) for this model can be the nation, state, one or more counties, or a sub-county. Users are allowed to specify when setting the attributes.

3) The temporal coverage for this model runs from 1970 through to 2050. This means that the model can estimate past-, current-, and future-year emissions. Relevant growth and scrappage rates for equipment also are employed to estimate past- and future-year emissions. Further, the time period for emissions can be restricted to a particular year, season, or month.

4) The basic model inputs are equipment population, average load factors expressed as the average fraction of available power, average power in horsepower, activity in hours of use per year, and emission factors with regard to deterioration and/or new standards.

5) The output report is realized by Microsoft ACCESS. It provides emission totals by county, equipment type, horsepower, etc. This is selected by the user. The model also can enable users to compare the results of two separate model runs.

Obviously, this model has advantages with regard to the estimation of emissions from a macro perspective. For micro goals, such as for a particular construction project's emissions, it is not adequate or sufficiently detailed. This is because: 1)

the most detailed geographic level is the sub-county. The model estimates

emissions for an area which may have several simultaneous projects, yet this

"several" is gained through estimation rather than actual events; 2) the time period

for emissions cannot be set to a definite and limited time range (such as from May

15th to August 22th) and equipment activity hours are assumed; 3) the model

covers most construction equipment, but each piece of equipment is provided with

only one emission factor and a value that is an average for its type. Average load

factor, which is the key to obtaining emission factors, represent only the typical

operating load fraction for equipment. Equipment can be used during several

kinds of duty cycles (e.g., excavate soil, strip topsoil, move rock, etc.), however,

and the type of duty cycle depends on the project's work content. From a micro

perspective, a single load factor thus is not sufficient for an estimation.

1.2.2 California off-road model

This model was developed by the California Air Resource Board (CARB) to

estimate emissions from off-road sources in California (Figure 2). It can forecast

exhaust emissions (CO_2, CO, NOx, etc.), evaporate (refueling, diurnal, hot soak

losses, etc.) and toxics (lead, cadmium, mercury, etc.) for 94 types of equipment

within 17 categories (such as recreational, construction and mining, and lawn and

garden equipment). Emission outputs are provided according to fuel type, engine

type, horsepower group, geographical location, etc. This model also incorporates

various aspects of off-road equipment emissions, such as the effects of

regulations, technology, and seasonal conditions, into its estimates (CARB

2006a).
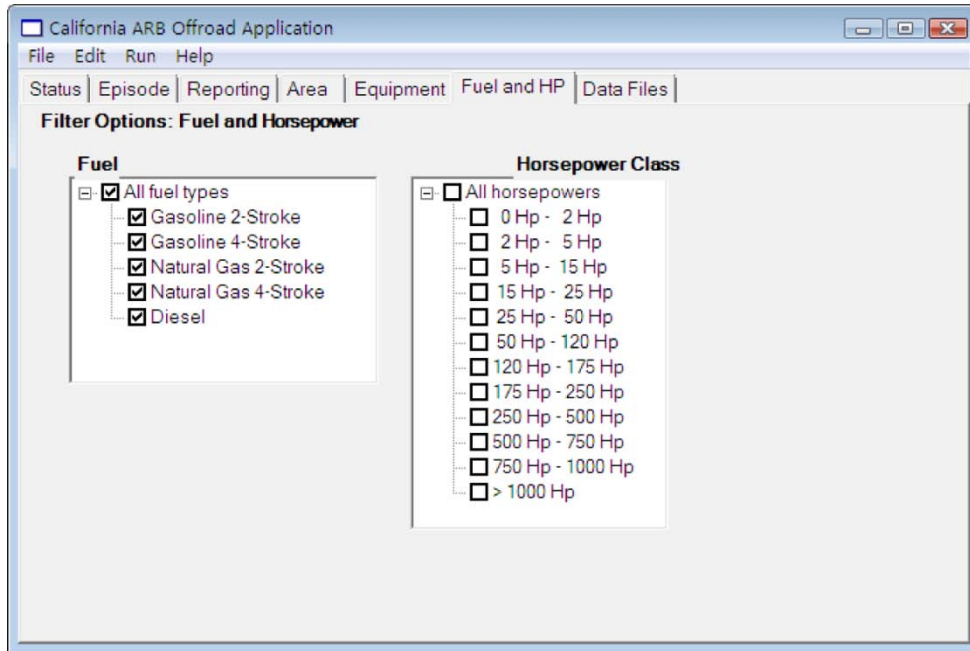
Figure 2: The operational interface of the California ARB off-road model (CARB, 2006a)

The off-road model uses the same methodology as the EPA's non-road model to

obtain emission output. Emission amounts are found by multiplying emission

factors (g/bhp-hr) with population, load factor, activity (hrs), and average

horsepower (hp). As with the non-road model, the off-road model considers

spatial and temporal features; it is more detailed, however, since the model is

geographically restricted to California.

As for exhaust emission-factor inventories, they are affected by engine type, fuel type, horsepower, and model year. This is similar to the EPA's non-road model. However, off-road emission factors are adopted from the CARB's official data inventory, whereas the EPA's non-road model draws its data from the nation as a whole.

CARB's model thus is better suited to California, since it accurately reflects the actual conditions in the state. It functions similarly to the EPA's non-road model: it also is a macro-level tool that can estimate emissions. It suffers from the same restrictions as those examined in the analysis of the EPA's non-road model, however.

1.2.3 Emfac2007

To complement the non-road model, CARB designed Emfac2007 to calculate emission factors (e.g., g/miles) for motor vehicles that operate on California roads. The referred vehicle list includes heavy-duty trucks, which are often used in construction. Figure 3 is the user interface snapshot of Emfac2007.
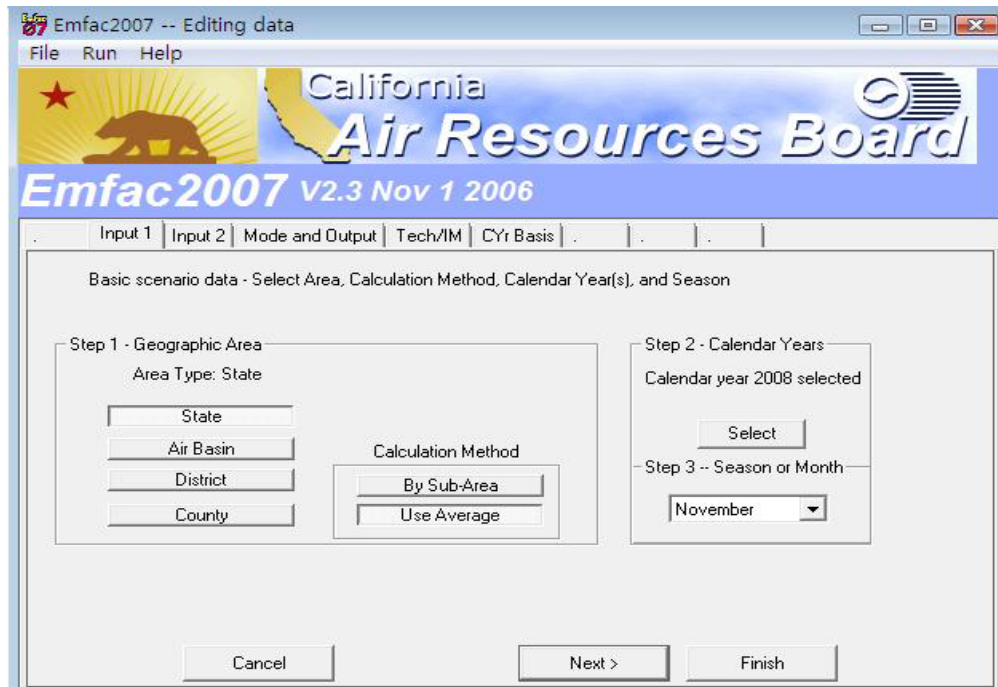
Figure 3: The operational interface of Emfac2007 (CARB 2006b)

The features of Emfac2007 are described below (CARB 2006b):

1) Besides the regular gases featured in the non-road model, Emfac2007 includes lead (Pb).

2) Heavy-duty trucks are the only equipment referred to in this model that are used in construction. The model can provide two exhaust processes for this equipment: running and idle exhaust. Running exhaust represents emissions that come out of the vehicle tailpipe while it is traveling on a road. Idle exhaust, in contrast, refers to emissions that come out of a vehicle tailpipe while it is operating but not traveling any significant distance (as with the loading or unloading of goods).

3) Emfac2007 provides relevant data for equipment within the model years of 1960 to 2040.

4) The geographic area includes basins, districts, and counties within California. Temporally, it is similar to the non-road model. Users can select emission estimations for the years 1970 to 2040 and for year, season, or month within this range of years.

5) The main inputs required to get emission factors are geographic area, calendar year, month or season selection, model year, inspection and maintenance programs, and output options. Users can further modify for attributes such as temperature, vehicle speed, humidity, and so on.

6) Emfac2007 can provide emission factors such as grams of pollutant emitted per vehicle activity or tons of pollutant emitted per weekday, etc.

Emfac2007 is designed to get emission factors for on-road equipment only and is restricted to California. However, its calculation method for heavy-duty trucks can be used as a reference, since it differentiates between running emission factors (g/mile) and idling emission factors (g/idle hour). Emission estimation accuracy could be increased further if these two aspects of emission factors were included in the evaluation of pollution from a detailed project. Emfac2007 is still a macro-estimating tool, however, since equipment activity hours, population, miles

traveled, etc., are still taken from statistics. Like the non-road model, it is not a project-based emission estimating method.

1.2.4 The road construction emission model

The Sacramento Metropolitan Air Quality Management District (SMAQMD) built a road construction emission model to assess daily emissions from linear road construction projects. This model is designed to implement regulations intended to restrict the daily production of NOx from any construction project to 85 pounds (SMAQMD 2009a). Figure 4 is the interface for the model.

Figure 4: The operational interface of the road construction emission model
(SMAQMD 2009b)

The features of the model are described below (SMAQMD 2009b):

1) It is designed in Microsoft Excel to be easy to use.

2) It is a project-oriented tool. The data entry requires project-specific information, such as soil type, average truck capacity, number of round trips, etc. The estimation is realized by analyzing emissions from four phases of road construction (grubbing/land clearing, grading/excavation, drainage/utilities/sub-grade, and paving) within which different combinations of equipment may be used.

3) The emission factors embedded in the model combine the databases from both the California off-road model and Emfac2007.

4) The model's output provides daily emission totals.

While this model emphasizes the features of specific projects, it is limited to road construction. The output of daily emissions records whether a project has exceeded Sacramento's daily NOx emission limits. In this way, the model reveals the importance of daily emission estimation for all types of construction projects.

1.2.5 Life-cycle assessment (LCA)

The International Standards Organization (ISO) (1997) defines life-cycle assessment (LCA) as a method for assessing the environmental impact of a

product or process through its entire life cycle, from raw material acquisition to production, use, and disposal. It is dissimilar to the models previously discussed, since it does not focus on how to calculate emissions but serves as a comprehensive and conceptual framework to evaluate emissions.

The construction industry has widely applied LCA methods to investigate the environmental impact of the life cycle of commercial and residential buildings (i.e., from raw construction material production to building maintenance). Process-based LCA and Input-Output LCA (I-O LCA) are the two types of LCA methods that effectively evaluate construction processes (Ahn et al. 2010a). Process-based LCA estimates environmental inputs and outputs within each process according to the process flow. It addresses process-specific issues. I-O LCA uses transaction data among the sectors of an entire economy and provides ideas in a general manner. Hybrid approaches often are designed in academic research to realize the advantages of each method. For example, Guggemos and Horvath (2006) used a process-based LCA and an EIO-LCA tool from Carnegie Mellon University to estimate the environmental impact of structural frame construction for four-story office buildings in California. They estimated that the project generated around 291 tonnes of CO_2, 2466 kg of NO_2, and 1997 kg of CO.

Due to the limits of data accessibility, however, it is difficult to gain adequate life-cycle data for construction processes from industry sources.

1.2.6 Lewis' algorism for calculating emission factors

Lewis (2009), investigated duty-cycle specific emission factors and fuel use rates for eight common types of diesel construction equipment with 17 corresponding representative duty cycles, in his PhD dissertation in North Carolina State University, U.S. Field data from a large number of job sites on or near the campus was collected for this investigation. The developed algorism estimates the emission factors of equipment while engaged in a specific duty cycle (e.g., the CO emission factor of an Excavator is 300 g/hr when excavating soil and 250 g/hr when moving soil). This is done by assessing the fuel consumption of equipment in that duty cycle and then converting the fuel use rate to emission factors. The biggest advantage of this database is that it is capable of differentiating emission factors of different duty cycles for diesel construction equipment. A single detailed project involves several types of equipment with assigned duty cycles. With a tool that can provide reliable accumulative duration data for each duty cycle, it is possible to estimate accurately the project's emissions by combining Lewis' database with the unknown tool. Since Lewis' method is quite new, it has not been generalized. More details on Lewis' algorism will be addressed in section 2.2.2.

1.3 Motivations and objectives

Current efforts to quantify emissions mostly utilize macro-level tools; micro-level emission estimation has not yet received much attention. Micro-level estimation refers to project- and operation-based and daily emissions. This type of estimation more effectively permits regulations (e.g., the Sacramento Metropolitan Air Quality District Management's daily NOx production limit of 85 pounds from any construction project (SMAQMD 2009a)) to be addressed and allows better project decisions on environmental sustainability to be made.

Discrete Event Simulation (DES) methodology, a new approach to estimate emissions (Ahn et al. 2010b), can be used as a micro-level method. DES can simulate a project or operation by running chronological occurred events. The advantages of DES are obvious: it duplicates the as planned activities on the job site and estimates emissions from the simulated project or operation. DES is able to calculate more accurate durations for each work package, especially in large-scale and complex projects. It also offers several common distribution types to allow users to input stochastic values (e.g., duration). Accurate duration estimates lead to accurate emission estimates (emission amount = emission factor x duration). Further, it is able to include emission factors for different duty cycles and more accurately estimate utilization rates for equipment—on a real job site,

equipment emits gases so long as equipment operators keep their engines on, as when they are waiting in a queue. Emissions also vary based on workload. For example, a bulldozer should have four different emission factors for its three representative duty cycles: rough grade, fine grade, stockpile, and idling state. DES permits simulation properties and model elements to be set easily and modified according to user wishes. Simulation outputs from different perspectives, such as obtaining the daily emission output by setting the simulation time to 8 hours or comparing the outputs of two scenarios by changing a model element or sequence, thus can be obtained.

A thesis objective is to develop a DES methodology that can estimate individual, facility-specific emissions from the construction process (micro estimating). Through output estimation, users can get a better idea of the volume of emissions that will be produced on the basis of an activity, daily production, or project. People then can adopt strategies to reduce emissions effectively, meet policy requirements (1-day limit), or even gain monetary benefits through the comaparison of scenarios.

In addition to DES, an emission federate within an environment of high level architecture (HLA) was designed for this research. HLA is a general purpose

architecture for distributed computer simulation systems (IEEE 1516 2010). It separates emission estimation from the whole simulation package, thus avoiding the need to build the models that are necessary in the DES method. Once other components (e.g., operation federate) are defined, users concerned with emissions need only to run all federates (including the emission federate) in the HLA. The emission federate will reflect information from the other federates and obtain the emission outputs. The HLA methodology is easiest for users; it requires extra federates to reflect job operation plans, however.

1.4   Framework

The design of a DES emission-estimating tool that uses the special purpose simulation (SPS) tool in the Simphony environment is the core framework of this research. Two case studies are presented to demonstrate the practicability and benefits of this tool with regard to emissions: an aggregate operation project (Farrar 2003) and an earthmoving operation in a tankfarm earthwork project in Regina, Canada. The aggregate operation project case study serves as a guide for using the DES tool to build models step-by-step. In addition to the DES method, the HLA federate section presents the basic principles, features, and user guides for the emission federate.

1.5   Scope

This research examines a single GHG (CO_2) and three CAPs/CACs (CO, NOx, and PM), as well as an additional pollutant type (HC). Most construction equipment engines are categorized as non-road, with diesel-cycled engines predominate. The equipment selected for analysis thus are typical diesel engine construction equipment (backhoe, dozer, excavator, off-road truck, grader, wheel loader, track loader, and crane).

Chapter 2: The DES Simulation[1]

2.1   The simulation software background

The DES software used in this research is Simphony 1.1.3.14 (http://irc.construction.ualberta.ca/html/research/software/simphony.net.html), which is an integrated environment developed at the University of Alberta that facilitates the creation of special purpose simulation (SPS) tools for modeling construction systems (Hajjar and AbouRizk 1999). The special purpose template developed for emissions estimation contains a set of modeling elements, which permits users to build models according to specific job plans. Modeling elements are connected with relationships.

AbouRizk and Hajjar (1998) define SPS as a computer-based tool which incorporates the given domain knowledge into the modeling process, so that it is useful for a practitioner familiar with the domain but inexperienced in simulation. This is the difference between SPS and general purpose simulation (GPS)—GPS contains only process modeling and cannot easily get domain-related outputs (AbouRizk and Hajjar 1998). SPS thus enables users to feel closer to the

---

[1] A version of this chapter (section 2.1 – 2.4) has been accepted for publication: Estimating Hazardous Gas Emissions from Construction Equipment Using Special Purpose Simulation in "The Constructed Environment International Conference," Venice, Italy, November 17 ~ 19, 2010. The same paper also has been submitted for publication in *The International Journal of the Constructed Environment.*

simulation.

In this research, the given domain mentioned above is emissions estimation. Users build models based on job plans with the template's modeling elements. The accumulated duration of each duty cycle and idling state from equipment then is collected. The final emission amount is determined by multiplying auto-generated emission factors with accumulated durations. The emission factors are calculated with the internal database of the template. This special purpose simulation tool therefore consists of three parts: the database for emission factors, the emissions estimation template, and the simulation model.

2.2   The database for emission factors

2.2.1 EPA 2004 database

The main emission factors database adopted in this research is the EPA's (EPA 2004a), which was designed for compression ignition diesel engines. This inventory is currently the most authoritative and widely-used database for emission estimation. The EPA non-road model, the California Air Resources Board's OFF-ROAD model, and other mainstream models all use it as their internal database. However, this database assumes that equipment will have fixed emission factors at all times, regardless of duty cycle (Ahn et al. 2010c).

The general algorism of the EPA 2004 database is displayed in Figure 5. The equation for getting CO, HC, and NOx emission factors from the EPA database is: emission factor = EFss $\times$ TAF $\times$ DF (EFss is the zero-hour, steady-state emission factor in g/hp-hr; TAF is the transient adjust factor; DF is the deterioration factor). The PM emission factor needs to subtract a value for fuel sulfur content (S_{PMadj} is the sulfur adjustment for PM emissions) based on the preceding equation. The CO_2 emission factor is a little different, since it is calculated based on brake-specific fuel consumption (BSFC) and is closely related to the HC emission factor in the EPA's method (CO_2 emission factor = (BSFC $\times$ 453.6 − HC) $\times$ 0.87 $\times$ (44/12)). Given the EPA emission factors (g/hp-hr or kg/hp-hr (only for CO_2)), this equation can be used to obtain emission amounts (emissions = engine population $\times$ engine horsepower $\times$ load factor (load factor refers to fraction of available power) $\times$ activity duration (hr) $\times$ EPA emission factor ((k)g/hp-hr)). For example, ten 300-horsepower trucks work for 20 hours. The load factor for each truck is 0.59, the EPA emission factor is 1.42 g/hp-hr for CO emission, and the total CO emission is calculated as: 10 $\times$ 300 $\times$ 0.59 $\times$ 20 $\times$ 1.42 = 50268 grams. This means that the ten trucks have emitted more than 50 kg of CO.

In order to unify the unit of emission factors to grams per hour (g/hr) or kilograms

per hour (kg/hr for CO_2 only), the redefined emission factors of the EPA database

in this research are equal to the EPA emission factors ((k)g/hp-hr) multiplied by

engine horsepower (hp) and load factor. The redefined emission factors thus are:

(k)g/hr = EPA emission factors ((k)g/hp-hr) × horsepower (hp) × load factor.

The details of the EPA 2004 database's algorism can be better understood by

reviewing EPA documents (EPA 2004a) (EPA 2004b).
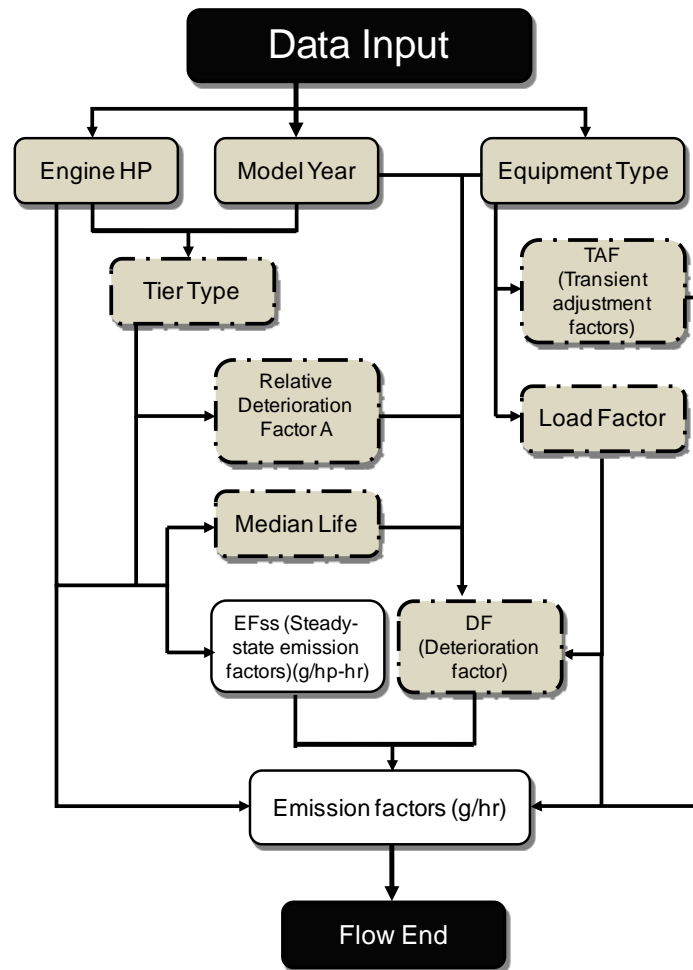
Figure 5: The process logic of the EPA's 2004 emission factor database

2.2.2 Lewis' database

As introduced previously, DES allows separate emission factor entries for different duty cycles of the same equipment. The ideal emission factors database for DES needs to be able to differentiate duty cycle emission factors. Lewis' database (2009), another database option in this method, therefore suits the simulation-based method presented in this research. Its estimations have relatively large discrepancies compared with the EPA's database due to a different test method, algorism, and equipment coverage. These will be illustrated further in the case study.

The algorism of Lewis' database is displayed in Figure 6. The unique feature of this database is to divide an engine's operation into ten modes, each of which represents a kind of load state (mode 1 refers to an empty load state or idling state; mode 10 refers to a full load state). The fuel use rate for each mode is determined by the equipment's horsepower. Each specific duty cycle for the equipment has a specific fraction of time spent and fuel used in each mode. By combining the given emission rate per unit of fuel consumed (g/gal) and the weighted-average fuel use rate (gal/hr), the emission factors (g/hr) for air pollutants can be determined for each duty cycle. An on-board portable emission monitoring system (PEMS): Montana system, was applied to get fuel use and

emission data, together with a laptop which recorded the information on equipment's activity modes (Lewis 2009).
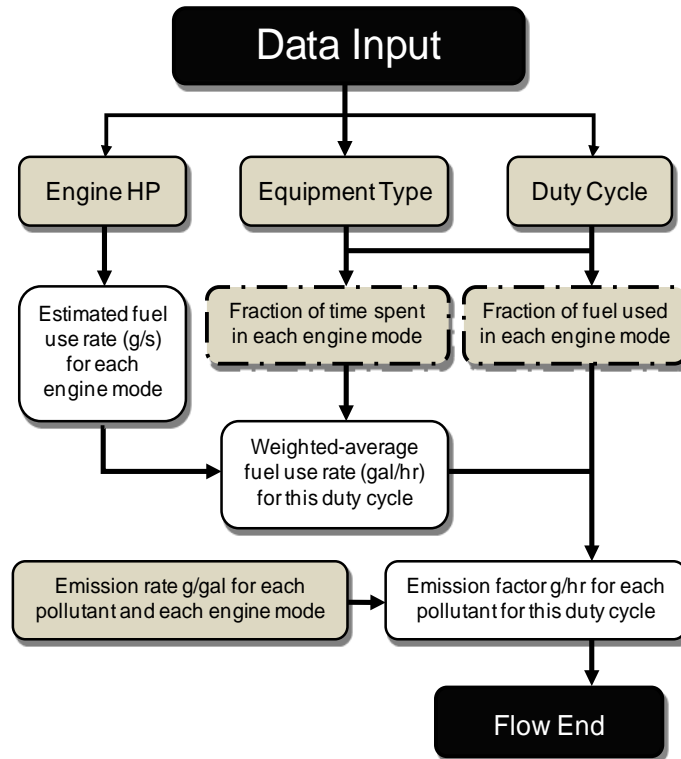
Figure 6: The process logic of Lewis' emission factor database

2.2.3 Others

If preferred, practitioners can manually input their preferred emission factors instead of using either the EPA's or Lewis' database. They could, for example, be the user's own tested emissions factors for their fleet of construction equipment.

2.3 The special purpose templates

Simphony models are constructed from modeling elements. A collection of these

elements that belong to the same construction domain and are designed to work

together in a model is referred to as a template (AbouRizk and Mohamed 2000). In

this research, a template called "HazardousGasEmissions" was created to

estimate emissions. It includes three modeling elements: resource,

DieselEnginesEmissions, and sum. These elements were developed in

VisualBasic. Figure 7 displays the template icons for these three elements.
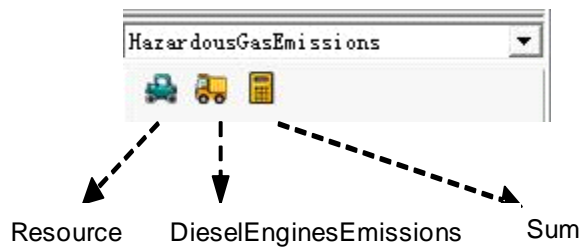
Figure 7: The "HazardousGasEmissions" template element icons

2.3.1 Resource element

The Resource element represents one type of resource which will be captured

and released to perform tasks (duty cycles) in the model. Generally, "resource"

refers to equipment and is used to record emission-related attributes. Since

each capture or release during the model run affects the utilization rate of the

resource, the Resource element also can record idling emissions (Figure 8).

Resource(122) Properties	泊 ＞
Outputs	
Current	1
EmisCO	35.9976
EmisCO2	6.72408
EmisHC	**18.3384**
EmisNOx	**105.9552**
EmisPM	**0.672408**
IdleFuelUseRate	**0.6792**
IdleTime	**1635.94153316209**
SimTime	2000
Tier	**Tier 2**
Parameters	
EmissionFactors	LewisDatabase
EngineHP	349
EngineYear	2006
EquiType	WheelLoader
ResName	loader
Total	1
Statistics	
CO2kgGHG	**Statistic**
COg	**Statistic**
FuelConsumption	**Statistic**
HCg	**Statistic**
NOxg	**Statistic**
PMg	**Statistic**
Utilization	**Statistic**

Figure 8: The template icon and properties window of the resource element (e.g., wheel loader)

Input parameters:

1) EmissionFactors: provides a list of available emission factor choices for this resource's idling state. Users can select "EPA 2004" or "LewisDatabase", or they can select "YourPreferredEmissionFactors" and manually input their own emission factors. If this resource does not emit when idling, users can select "NoNeed".

2) EngineHP: engine horsepower of the equipment (in hp). Equipment horsepower is usually in direct correlation to emissions.

3) EngineYear: model year of the equipment. Older equipment is not as environmentally friendly as newer equipment.

4) EquiType: equipment type of the resource. Choices are wheel loader, track loader, backhoe, off-road truck, bulldozer, excavator, moto grader, and crane.

26

Different types of equipment have different emission profiles.

5) ResName: name of the resource. This is a user-input label to conveniently identify the desired resource when choosing a resource to be captured or released during the modeling process.

6) Total: total quantity of this type of resource.

Outputs:

1) Current: current number of the available (i.e., idling) resources. When a resource is captured or released, the current quantity will decrease or increase, respectively. The capture element and release element will calculate this value.

2) EmisCO/CO$_2$/HC/NOx/PM: calculated idling emission factors for each air pollutant for this resource (kg/hr for CO$_2$ and g/hr for the rest).

3) IdleFuelUseRate: calculated idling fuel-use rate for this resource (gal/hr).

4) IdleTime: accumulated idle time of this resource. It is calculated with the utilization rate and total simulation time.

5) SimTime: simulation time of the model.

6) Tier: tier type—users can check the emission standards published by the EPA (EPA 2004a) to obtain tier type information for their equipment.

Statistics:

1) CO_2/CO/HC/NOx/PM: emission amounts produced in the idling state of this resource (kg for CO_2, g for the rest). It is obtained by multiplying idle time with idling emission factors.

2) FuelConsumption: fuel consumption amount produced in the idling state of this resource (gal). It is obtained by multiplying idle time with the idling fuel use rate.

3) Utilization: resource utilization rate as a percentage. The WaitingFile element will calculate it according to this resource's current value.

(The statistics, except for utilization, can be displayed as cumulative time-based curve graphs.)

2.3.2 DieselEnginesEmissions element

This element represents a duty cycle (task) performed by diesel equipment. It collects a piece of equipment's accumulated duration for the duty cycle and calculates the emission amount produced during the cycle (Figure 9).

DieselEnginesEmissions(21) Properties	
Outputs	
AccuDur	23.7159767863767
EmisWtAvgCO	173.2728908736
EmisWtAvgCO2	**40.292950074048**
EmisWtAvgHC	72.35043572736
EmisWtAvgNOx	**510.0145483104**
EmisWtAvgPM	4.0913210999808
FuelWtAvg	**4.001683392**
SimTime	**206.227529462294**
Tier	**Tier 2**
Parameters	
Description	loading
Duration	**Triangular(2, 3, 4)**
EmissionFactors	LewisDatabase
EngineHP	349
EquiType	WheelLoader
NumSrv	0
WlDutyCycle	LoadTruck
WlEngineYear	2006
Statistics	
CO2kgGHG	**Statistic**
COg	**Statistic**
FuelConsumption	**Statistic**
HCg	**Statistic**
NOxg	**Statistic**
PMg	**Statistic**

Figure 9: The template icon and properties window of the DieselEnginesEmissions element (e.g., wheel loader)

Input parameters:

1) Duration: duration of the duty cycle (distributions are allowed).

2) EmissionFactors: very similar to the Resource element. The only difference is that "SameAsResource" is substituted for the "NoNeed" option in the pull-down menu. This option will tell the system that the emission factors to be used in this duty cycle will be the same as those in the corresponding resource element. This helps users to avoid the repeated input of emission factors if they decide to apply the same emission factors (e.g., the EPA's database) for equipment regardless of duty cycles and idling states.

3) Engine HP & EquiType: similar to the Resource element. As long as values

have been provided in the Resource element, users need only pick values in

the pull-down menu rather than manually inputting them again.

4) WLDutyCycle & WLEngineYear: the duty cycle that the equipment (in this case,

wheel loader) will perform and the model year of the equipment. WL is the

abbreviation for the wheel loader. Both input parameters will be generated after

the EquiType is defined (e.g., if excavator has been selected in EquiType,

ExDutyCycle and ExEngineYear will be generated).

Outputs:

1) AccuDur: accumulated duration of this duty cycle. It will total the durations for

every model entity that has passed through this element.

2) EmisWtAvgCO/CO_2/HC/NOx/PM: calculated (weighted average) emission

factor for each air pollutant in this duty cycle (kg/hr for CO_2 and g/hr for the

rest).

3) FuelWtAvg: calculated fuel use rate for this duty cycle (gal/hr).

Statistics:

1) CO_2/CO/HC/NOx/PM: the emission amount produced from this duty cycle (kg

for CO_2, g for the rest). It is obtained by multiplying the accumulated duration

with the emission factors from the corresponding duty cycle of the equipment.

2) FuelConsumption: the fuel consumption amount produced from this duty cycle

(gal). It is obtained by multiplying the accumulated duration with the fuel use

rate from the corresponding duty cycle of the equipment.

(Cumulative time-based curve graphs are derived from this element and provided

in Statistics.)

2.3.3 Sum element

This element helps to sum emission data from all DieselEnginesEmissions

elements (i.e., emissions from the duty cycle) with all Resource elements (i.e.,

idling emissions). See Figure 4.
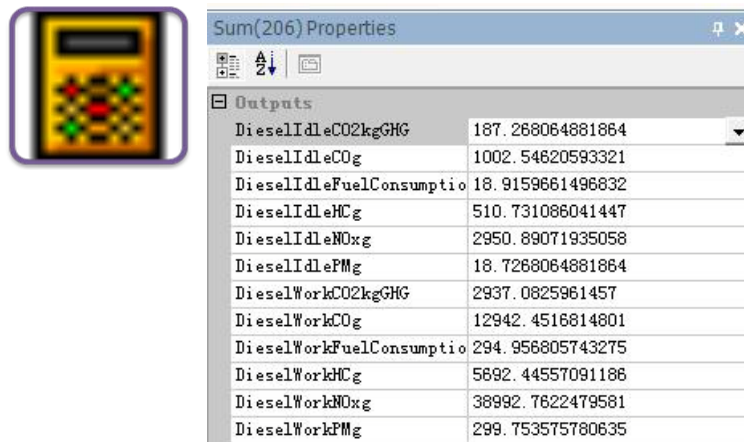
Figure 10: The template icon and properties window of the sum element

Outputs:

1) DieselIdleCO$_2$/CO/HC/NOx/PM/Fuel Consumption: the sum of data from all

Resource elements.

2) DieselWorkCO$_2$/CO/HC/NOx/PM/fuel consumption: the sum of data from all

   DieselEnginesEmissions elements.

2.4   The simulation model

Figure 11 shows the template selection area and central modeling area of the

Simphony interface (A: Template selection area; B: Central modeling area).

Users drag needed modeling elements from the special purpose template, found in

the template selection area on the left of the Simphony interface, to the central

modeling area.
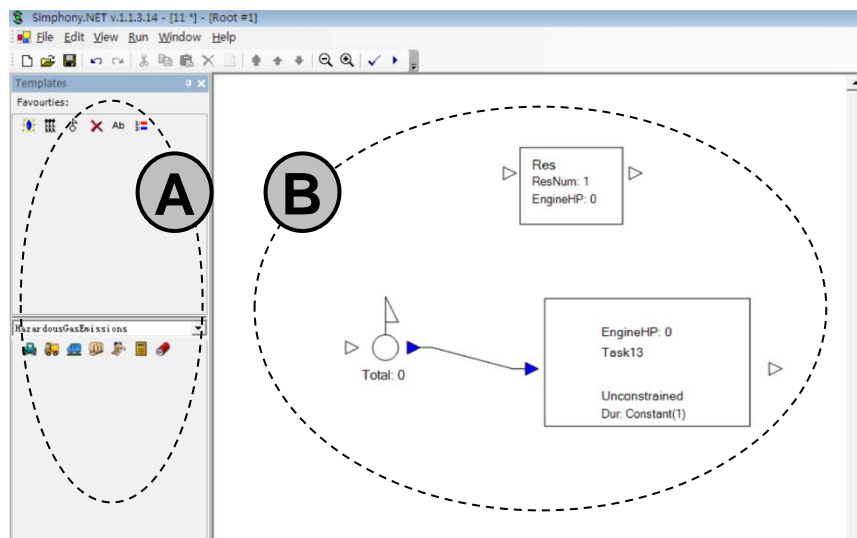
Figure 11: The Simphony interface

Figure 12 shows the Resource, Sum, and DieselEnginesEmissions element icons

in the modeling area. The Resource and Sum elements can be put anywhere in the

modeling area, without drawing any connection lines to other elements. Generally,

they are put at the top of the model for ease of recognition. The number of needed

Resource elements depends on how many types of resources (i.e., equipment) are necessary for modeling. Only one Sum element is needed.

(a)Resource element	(b)Sum element	(c) DieselEnginesEmissions element

Figure 12: The modeling icons for the Resource, Sum and DieselEnginesEmissions elements

The DieselEnginesEmissions element needs to be connected to another DieselEnginesEmissions element or to primary elements from the general template, depending on the work sequence (i.e., job working plan). These simple primary general template elements, including the NewEntity, Capture, Release, and WaitingFile elements, are necessary to support the building of an integrated model. They are quite easy to understand even if users have no experience with programming or simulation.

The NewEntity element creates entities, the number of which can be set by users. Entities, transferred out of the NewEntity element, truly enable the simulation. They will be explained in the following example (Figure 13):
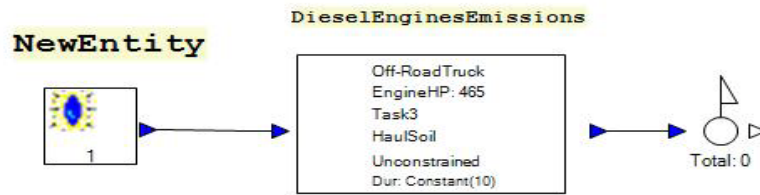
Figure 13: An example for explaining entities

When the simulation starts, one entity is created by the NewEntity element in the model. It then is transferred to the DieselEnginesEmissions element. Once the entity, after 10 units of time spent (which is the duration of HaulSoil), transfers from that element, the truck will have finished "Task 3".

The Capture and Release elements are used to capture and release resources (Hajjar and Mohamed 2007). Resource capturing happens before a duty cycle. The resource then is processed and released once it has finished its duty cycles. As soon as the resource is released, it is available and ready to be captured again.

Like the Resource and Sum elements, the WaitingFile element also needs to be dragged to a random place in the modeling area. The WaitingFile represents the waiting queue for the resource that will be captured by the Capture element, which will ask for a specific WaitingFile to capture a resource. This WaitingFile then will acquire the resource's utilization rate. In any model, each capture has a corresponding WaitingFile. Figure 14 is a typical small simulation model which

includes these elements.
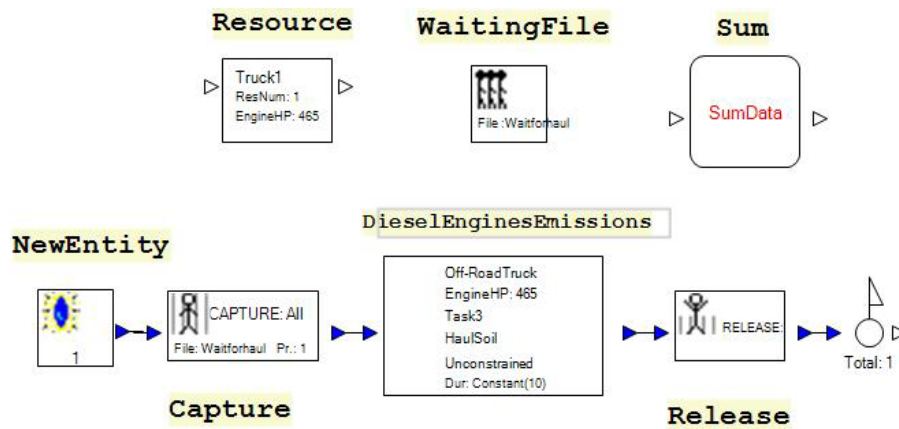
Figure 14: A typical simulation model involving the above mentioned elements

Details concerning how to build a model with a combination of special purpose template and general purpose template primary elements will be illustrated in the aggregate operation case study.

The DES tool has been verified for both emission factor databases by manual calculation in Microsoft Excel. The manual calculation results are the same as for the simulation run. This demonstrates that the internal calculation code for the template is correct.

2.5   The DES's validation framework

This section aims to create a validation framework, which is the suggested sample for testing whether the DES tool is able to correctly estimate the durations (especially the idle durations). The emission estimation would be reliable with a chosen emission factor's database if the durations are simulated precisely. A small-scale typical earthmoving operation by the North America Construction Group (NACG) was selected as an example for the validation framework. The operation was located in Regina, SK, Canada. Due to the complexity of obtaining other air pollutants' data, CO_2 is the air pollutant selected for validation, because stoichiometry provides available methods for converting fuel consumption to CO_2 emissions and the fuel consumption is easy to detect.

The process of the validation framework is shown in the Figure 15. Following the field activity plan, the simulation model was built on the basis of the emission template in Simphony. Portable devices were installed in the equipment to collect duration data and fuel consumption information. The fuel consumption data was measured as grams per hour (GPH), which can be converted into CO_2 emission factors by stoichiometry. The CO_2 emission factors for different duty cycles were input into the simulation model, thus producing the simulated output of CO_2 emissions. This then was compared with emissions from the actual operation. If

the result of the comparison was positive, the simulation model would be proved

to correctly measure equipment durations for this operation.
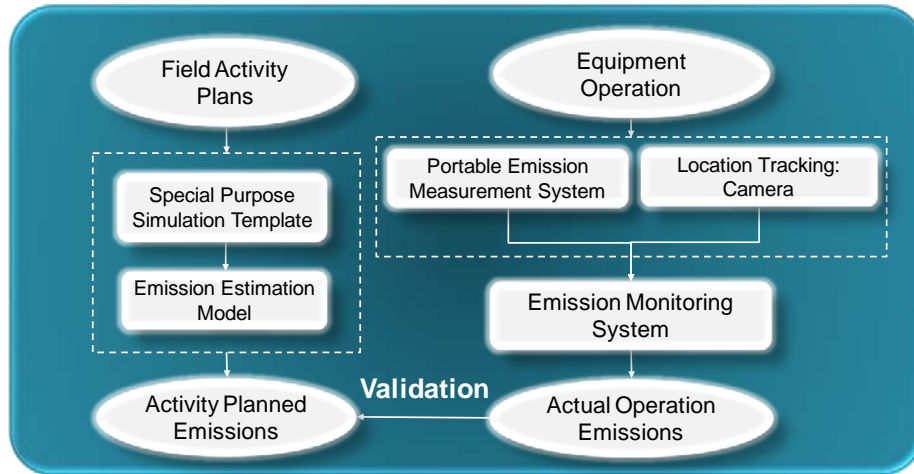
Figure 15: Process of the validation framework (Pena-Mora et al. 2008)

2.5.1 Operation

The CAT 740 trucks (Figure 16)' operation No. 1 (10:24 am ~ noon, May 13th,

2010) is a typical truck operation (Figure 17). There were three Caterpillar (CAT)

740 trucks and one Hitachi excavator. The site visit of validation aimed at

measuring one truck's CO_2 emissions because the measuring devices for Hitachi

machines were not accessible at that time. Figure 16 shows how it worked on the

site:

Figure 16: The monitored CAT 740 truck
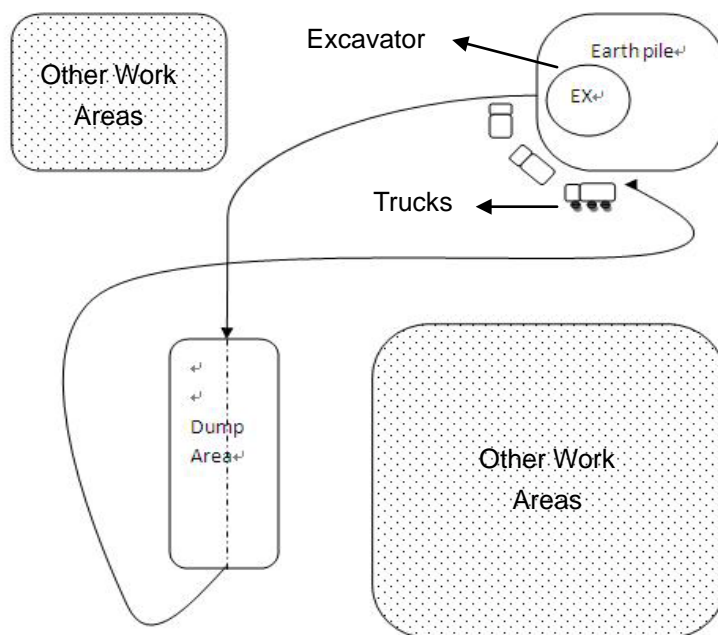
Figure 17: The trucks' site operation

Each truck has 6 states: loading ---- hauling --- dumping --- returning --- waiting in the queue --- attach to the excavator. The excavator had a self-check before the monitored truck was attached to it in the 2nd work cycle. The trucks in this state are considered to be waiting. The trucks' demobilization, in contrast, is considered to be returning. Figure 18 is the flow chart for each truck's operation.
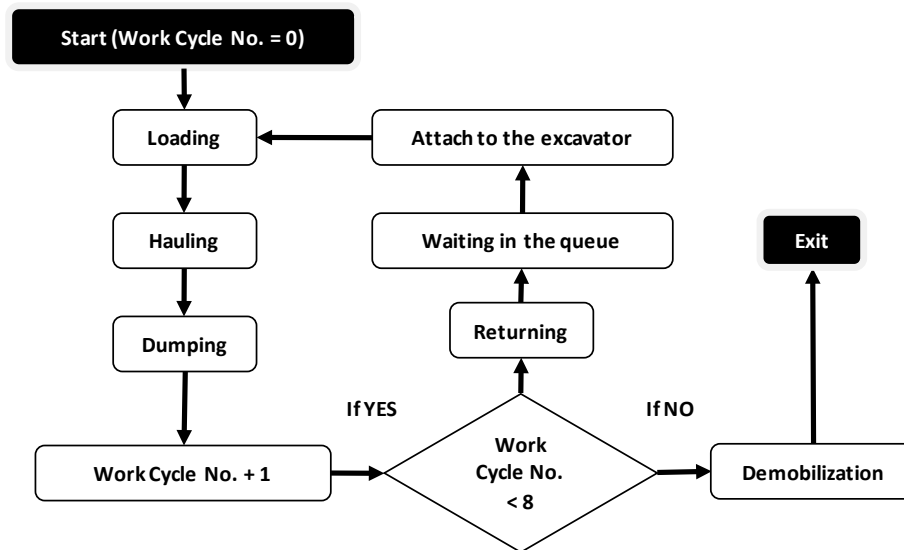
Figure 18: The flow chart of each truck's operation

2.5.2 Devices

The monitoring device box for CAT machines borrowed from NACG includes a CAT data logger (Figure 19) and a CAT laptop. The data logger connected to the truck is responsible for transferring the equipment's fuel burn use rate data (GPH) to the laptop. The special software in the laptop shows the data but requires the experimenter to record manually while sitting inside the truck cabin during the

operations. An extra converter is necessary to provide power to the laptap from

the truck. A video camera was installed inside the cabin to record the duty cycles

of the truck. The experimenter sitting inside the truck also recorded the durations

of each duty cycle.

Figure 19: The CAT data logger

2.5.3 Collected data & data analysis

2.5.3.1 Duration data (min)

2.5.3.1.1   Collected data

The collected data set contains durations for each state (Table 2).

Table 2: Durations for each state of the monitored truck

State	Duration	State	Duration	State	Duration
loading	2.00	hauling	1.05	dumping	0.38
loading	3.08	hauling	1.08	dumping	0.33
loading	2.72	hauling	1.17	dumping	0.33
loading	1.88	hauling	2.42	dumping	0.30
loading	3.08	hauling	1.37	dumping	0.43
loading	2.55	hauling	0.75	dumping	0.42
loading	3.28	hauling	0.88	dumping	0.37
loading	2.12	hauling	1.08	dumping	0.28

State	Duration	State	Duration	State	Duration
returning	2.65	waiting	3.59	attaching	0.33
returning	1.92	waiting	4.10	attaching	0.37
returning	1.42	waiting	3.52	attaching	0.35
returning	1.80	waiting	3.07	attaching	0.33
returning	1.72	waiting	4.60	attaching	0.42
returning	2.42	waiting	3.72	attaching	0.40
returning	1.35	waiting	4.33	attaching	0.40

State	Duration	State	Duration
ex check[1]	4.98	demobilizating	0.90

Note:
1. Ex-check refers to the self-check process of the excavator.

2.5.3.1.2   Data distribution fit

The data that needs to be input into the simulation model will be fitted to a distribution. Because the simulation model simulates the duration of "waiting in the queue", the duration of "wait" does not need data analysis. The distribution fit software Easyfit Standard 4.3 is used. Any outliers in the data group are removed when inputting data into the software.

1) Loading duration: Sample size = 8. Assume the value of 0.2 for level of significance = 0.2.

   The best fit distribution: **Uniform (1.6519, 3.5256)**, K-S statistic = 0.13719

2) Hauling duration: Sample size = 7 (the outlier 2.42 is removed). Assume the value of 0.2 for level of significance = 0.2.

   The best distribution: **Triangular (0.63427, 1.08, 1.4681)**, K-S statistic = 0.17915

3) Dumping duration: Sample size = 8. Assume the value of 0.2 for level of significance = 0.2.

   The best distribution: **Uniform (0.26104, 0.44896)**, K-S statistic = 0.13303

4) Returning duration: Sample size = 7. Assume the value of 0.2 for level of significance = 0.2.

   The best distribution: **Beta (0.31762, 0.43704, 1.35, 2.65)**, K-S statistic = 0.1853

5) Attaching duration: Sample size = 7. Assume the value of 0.2 for level of

significance = 0.2.

The best distribution: **Uniform (0.30864, 0.43422)**, K-S statistic = 0.17011

2.5.3.1.3   Goodness of fit (K-S test)

According to the Table of K-S critical value in the Appendix, if K-S statistic < K-S

critical value, the distribution will be accepted.

Loading: K-S statistic = 0.13719 < K-S critical value = 0.358

Hauling: K-S statistic = 0.17915 < K-S critical value = 0.381

Dumping: K-S statistic = 0.13303 < K-S critical value = 0.358

Returning: K-S statistic = 0.1853 < K-S critical value = 0.381

Attaching: K-S statistic = 0.17011 < K-S critical value = 0.381

All the fitted distributions are accepted. However, the sample size is relatively

small. The reliability of the distributions would increase if the sample size was

larger. The accepted distributions are shown in Table 3:

Table 3: The fitted duration distribution for each truck state

Truck State	Fitted Duration Distribution
loading	Uniform (1.6519, 3.5256)
Hauling	Triangular (0.63427, 1.08, 1.4681)
Dumping	Uniform (0.26104, 0.44896)
Returning	Beta (0.31762, 0.43704, 1.35, 2.65)
Attaching	Uniform (0.30864, 0.43422)

2.5.3.2 Fuel burn rate data (GPH: gallon per hour)

2.5.3.2.1 Collected data

Table 4: The GPH data for each state of the truck

State	GPH	State	GPH	State	GPH	State	GPH
hauling	8.9	dumping	5.8	returning	14.6	attaching	4.9
hauling	8.7	dumping	4.8	returning	15.2	attaching	3.9
hauling	6.7	dumping	5.2	returning	17.2	attaching	3.8
hauling	14.2	dumping	5.5	returning	13.1	attaching	4.3
hauling	10.8	dumping	4.5	returning	14.5	attaching	4.2
hauling	9.8	dumping	5.9	returning	14.9	attaching	3.9
hauling	10.2	dumping	5	returning	14.3	attaching	3.6
hauling	15.5	dumping	5.9	returning	16.2		
hauling	9.1	dumping	6.3	returning	11.3		
hauling	8.1	dumping	4.2	returning	9.8		
hauling	8.2	dumping	4.5				
hauling	7.8	dumping	5				
hauling	12.7						
hauling	9.6						
hauling	8						
hauling	10						

Note:
1. The collected GPH data for the truck state "waiting in the queue and loading" has a constant value of 0.2.
2. The data in this table contains data from another truck operation on the same day. The same truck was used in both operations, with the same carried earth load when hauling and dumping and empty load when returning. More data was collected for hauling, dumping, and returning in order to ensure more accuracy for the average value of GPH.

2.5.3.2.2   Representative data for each state:

Average values are taken to be representative GPH.

Table 5: The representative GPH (average values) for each state.

Truck State	Average GPH
loading	0.2
Hauling	9.89375
Dumping	5.325
Returning	14.1
Waiting in the queue	0.2
Attaching	4.085714

2.5.3.3 CO_2 emission factor (kg/hr):

$$4\,C_{12}H_{23} + 71\,O_2 \rightarrow 48\,CO_2 + 46\,HO_2$$
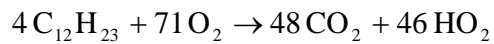
$$\frac{890\,\text{g}\,C_{12}H_{23}}{1\,\text{L}} \times \frac{1\,\text{mol}\,C_{12}H_{23}}{187\,\text{g}\,C_{12}H_{23}} \times \frac{48\,\text{mol}\,CO_2}{4\,\text{mol}\,C_{12}H_{23}} \times \frac{44\,\text{g}\,CO_2}{1\,\text{mol}\,CO_2} = \frac{2513\,\text{g}\,CO_2}{1\,\text{L}}$$

$$\frac{1\,\text{gal}}{1\,\text{h}} \times \frac{3.785\,\text{L}}{1\,\text{gal}} \times \frac{2.513\,\text{kg}\,CO_2}{1\,\text{L}} = \frac{9.511705\,\text{kg}\,CO_2}{1\,\text{h}}$$

The above formulas (R&D chemicals 2009) convert fuel burn rate (GPH) to CO_2

emission factors (kg/hr), which are shown in Table 6:

Table 6: CO_2 emission factor (kg/hr) for each state

Truck State	CO_2 Emission Factor (kg/hr)
loading	1.902341
Hauling	94.10643157
Dumping	50.64982913
Returning	134.1150413
Waiting in the queue	1.902341
Attaching	38.86210925

2.5.3.4 Fuel burn rate and CO_2 emission factor comparison

The CAT 740 truck's horsepower is 469hp (Caterpillar 2010) and the engine year is assumed to be 2002. With these attributes, the EPA emission factors (EPA 2004) can be obtained with the EPA's algorithm. This comparison (Table 7) gives an idea of the general difference between monitored and the EPA's data, which may not be accurate due to the assumption of years.

Table 7: The comparison of CO_2 emission factors and fuel burn rate

Truck State	Fuel burn rate (gph)		CO_2 Emission factor (kg/hr)	
	The collected data	EPA	The collected data	EPA
loading	0.2	11.42	1.902341	148.25
Hauling	9.89375	11.42	94.10643157	148.25
Dumping	5.325	11.42	50.64982913	148.25
Returning	14.1	11.42	134.1150413	148.25
Waiting in the queue	0.2	11.42	1.902341	148.25
Attaching	4.085714	11.42	38.86210925	148.25

2.5.3.5 Simulation model

The duration distributions, fuel burn rate, and CO_2 emission factors are input into

the simulation model (Figure 20).
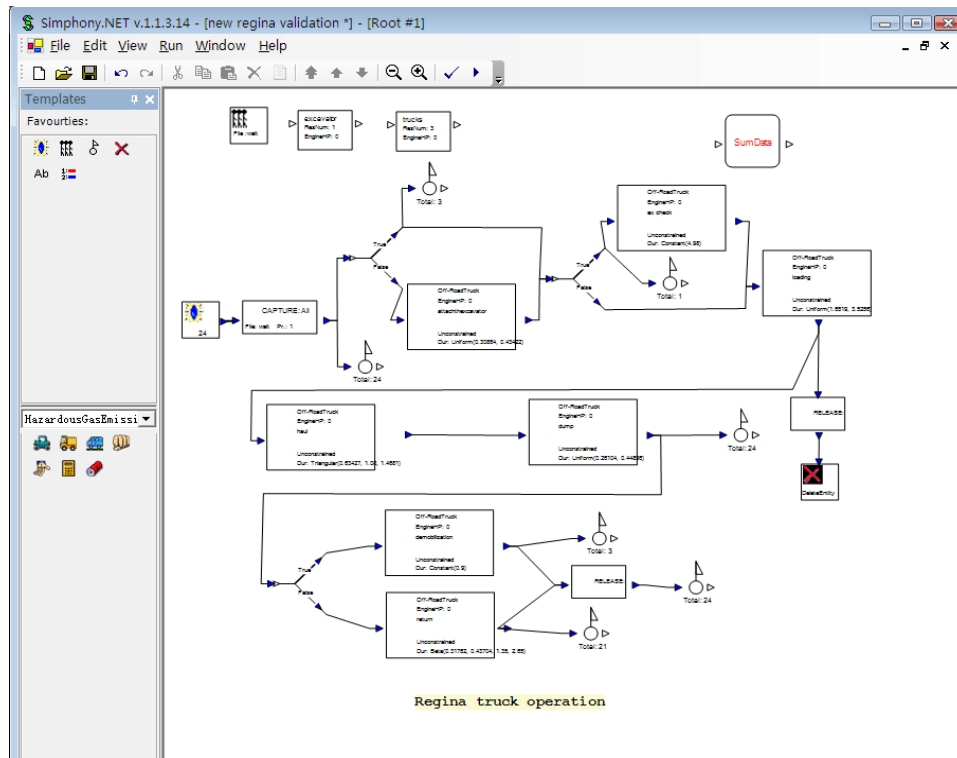
Figure 20: The simulation model of the truck operation

2.5.4 Data comparison

2.5.4.1 Monitored data:

Fuel consumption = Fuel burn rate (gph) $\times$ sum duration (hrs)

CO_2 emission = emission factor (kg/hr) $\times$ sum duration (hrs)

Because we could monitor only one of the three trucks, we assumed that each

truck had the same value for fuel consumption and CO_2 emission. So:

Total truck fuel consumption = one truck's fuel consumption $\times$ 3

Total truck CO_2 emission = one truck's CO_2 emission $\times$ 3

MS Excel 2007 was used to calculate the monitored data.

2.5.4.2 Simulated data:

MS Excel 2007 was used to record the simulated data from Simphony.

2.5.4.3 Comparison:

Table 8: The comparison of durations, fuel consumption, and CO_2 emissions

Truck State	All Trucks' Durations (hrs)		Difference %
	Monitored	Simulated (mean value of 20 runs)	
loading	62.13	61.54	0.95%
Hauling	29.4	25.43	13.5%
Dumping	8.52	8.46	0.70%
Returning	39.84	40.07	0.58%
Waiting in the queue	**80.79**	**79.54**	**1.55%**
Attaching	7.80	7.87	0.90%

Emission Output	The Truck Operation		Difference%
	Monitored	Simulated (mean value of 20 runs)	
Fuel Consumption (gal)	16.63	16.02	3.66%
CO_2 Emission (kg)	158.13	152.35	

2.5.5 Summary

The limitation is the data size (population) for duration analysis, which is only 7 to 8 data units. This is relatively small due to this operation's small size. However, the entire analysis method is the same when dealing with larger projects.

This truck operation produced 16.63 gallons of fuel and 158.13 kg of CO_2 emissions as we monitored it on the job site.

The comparisons (Table 8) show that the simulation model is very capable of estimating the emissions from real projects. The difference rate is 3.66% between the simulated and monitored outputs. The duration of "waiting in the queue" was especially accurate, with a 1.55% difference rate. This strongly demonstrates the accuracy of the DES model for estimating durations of different duty cycles on this project. For larger projects, duration calculations are very complex. The simulation would be even more helpful since it could achieve what manual calculations are unable to accomplish. In conclusion, this example demonstrates how the proposed validation framework can be applied to validate any specific projects. The steps described in the validation framework can be replicated for validating other projects.

Chapter 3: Case studies

3.1   Aggregate project[2]

This case study showcases the detailed steps for utilizing the SPS tool to simulate emissions. In addition, it illustrates how users can get benefits from various output analyses provided by the SPS tool.

3.1.1   Introduction and assumptions

Farrar (2003) developed a DES model to analyze the operational efficiency of the July 2000 Anthony Henday extension project in Edmonton, Alberta, Canada, which contained a typical aggregate placement operation. In this section, the introduced SPS tool is applied to model this aggregate operation case for estimating the emissions produced.

Farrar (2003) provides the work process of the aggregate operation together with collected duration data in distributions for each duty cycle. Three types of construction equipment were involved in that operation: aggregate truck, wheel loader and grader. Figure 21, modified from Farrar (2003), shows how the operation worked.

---

[2] A version of this section has been accepted for publication: Estimating Hazardous Gas Emissions from Construction Equipment Using Special Purpose Simulation in "The Constructed Environment International Conference", Venice, Italy, November 17 ~ 19, 2010. The same paper also has been submitted for publication in *The International Journal of the Constructed Environment*.
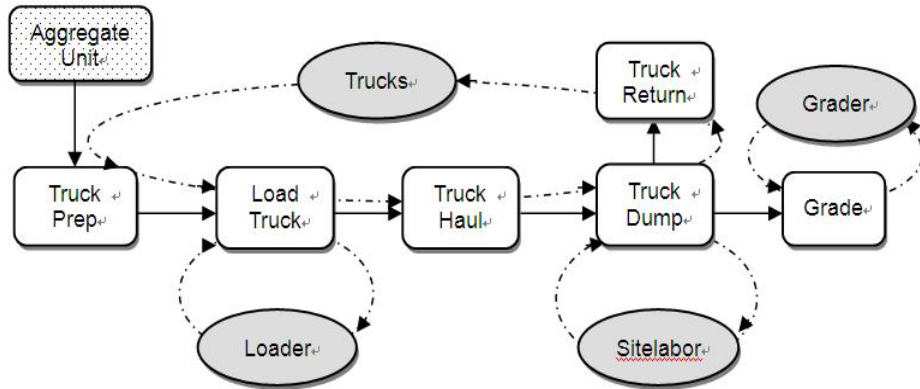
Figure 21: The flowchart for the aggregate operation (modified from Farrar 2003)

The entities created by NewEntity should refer to the aggregate units (a simulation conception), each of which would be represented by a number of tonnes of real aggregates. The number of tonnes should equal the capacity of aggregate trucks—in this model, the entities are carried by the trucks to the end. For example, if the truck capacity is around 30 tonnes of aggregates, one aggregate unit in the simulation would equal 30 tonnes of real aggregates. In order to simplify the simulation model presentation, we reduced the operation size by assuming 600 entities (around 18000 tonnes of aggregates) were created. Other assumptions are shown in Table 9.

Table 9: Other assumptions of the operation

Equipment	Engine HP	Engine Year	Quantity	EmissionFactor database
Aggregate truck	453	1999	23(given)	EPA's database (2004) or Lewis' Database (2009)
Loader	349	1999	1	
Grader	259	1999	1	
SiteLabor	NA	NA	1	

3.1.2 Build the model

Once the information and data are collected, the model can be built.

1) Four Resource elements should be added to this model (loader, trucks, SiteLabor, and grader) and their emission parameters should be set as "NoNeed" for SiteLabor and "EPA2004" or "LewisDatabase" for every other. The other parameters from Table 1 also are input.

2) One Sum element is applied to total the emissions.

3) The NewEntity is dragged into the model and the number of entities is set at 600.

4) As in the operation flowchart, the first duty cycle is truck preparation, which is performed by one of the trucks. A Capture element should be added right after the NewEntity, in order to capture one of the trucks to perform that duty cycle. Meanwhile, a WaitingFile named "waitforpre" is dragged to any place in the modeling area to represent the truck's queue to be captured for preparation. There are four steps to this capture: a) assign the FileName in the Capture

element to "waitforpre" so that the capture will link to that WaitingFile; b) set the NumofTypes as 1, since only one type of resource (trucks) needs to be captured in this capture; c) in Res1Method, choose the resource name; d) select "trucks" in the pull-down menu of Res1Name; this tells the simulation which resource this capture is going to capture. The Res1Num is 1 as default and does not need to be changed, since we will only capture one of the trucks.

5) Add a DieselEnginesEmissions element after capture. This element represents the truck preparation duty cycle. Parameters like duration, Engine HP, EquiType, etc., should be input into the corresponding blanks in the element.

6) Keep adding DieselEnginesEmissions elements, which stand for the subsequent duty cycles (truck load, truck haul, truck dump, grader grading etc.), until that resource finishes its one-loop jobs and is ready to go back to the initial duty cycle. For example, the initial duty cycle for truck is preparation and the following duty cycles are loading, hauling, dumping, and returning (which is the last duty cycle for the one-loop jobs for truck).

7) After the last duty cycle for each equipment ("returning" duty cycle for "trucks", "grading" duty cycle for "grader", and "loading" duty cycle for "wheelloader"), a Release element is required to release the resource so that the resource is available to be captured again for the next job loop. The steps to set the attributes of the release element are the same as those for the capture element

(steps b, c, and d).

8) According to the operation sequence, the whole model can be developed by following the steps above and logically connecting the elements with one another.

Figure 22 shows the model's outlook (A: truck duty cycle loop—prep, load, haul, dump, and return; B: loader duty cycle loop—LoadTruck; C: grader duty cycle loop—grade).
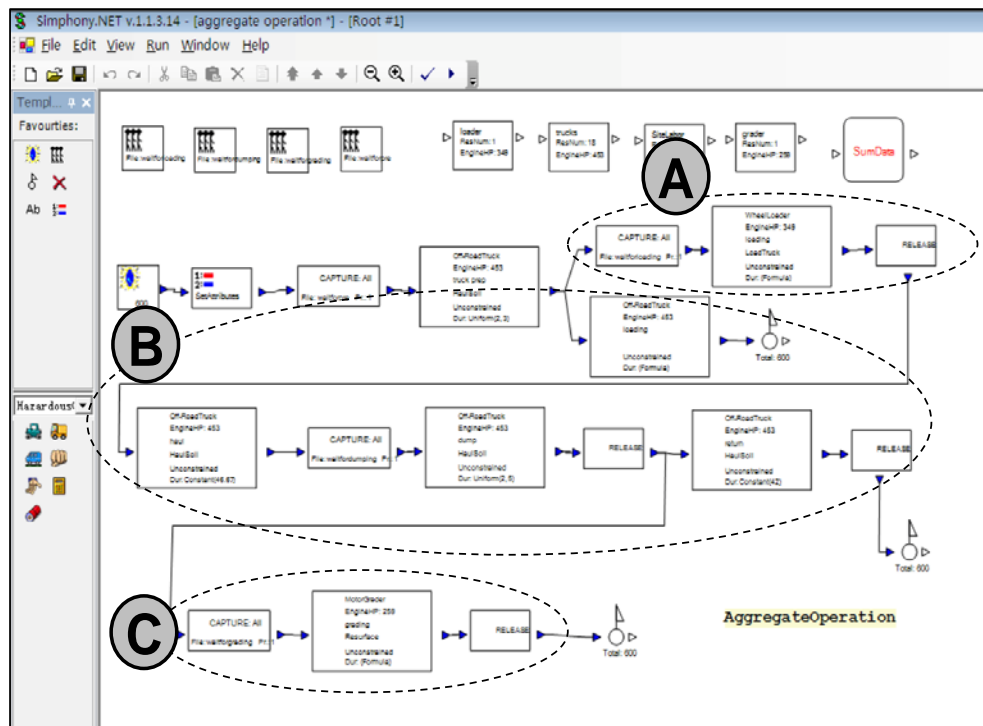
Figure 22: The built simulation model for the aggregate operation

3.1.3 Emission results for this aggregate operation

3.1.3.1 Emission factors for each type of equipment

Table 10 shows the emission factors' results from the simulation. Generally, emission factors from the EPA's are much larger than those from Lewis' database (2009). One explanation is that the EPA only provides a single emission factor for each air pollutant. For instance, idling emissions will be overestimated since idling emission factors should be far fewer than working emission factors. Another important factor is that the EPA's database covers most equipment, and Lewis (2009)'s data was collected from a limited number of equipment, which makes generalization difficult. The last reason for the outputs' difference of two databases is the source of getting emission factors. EPA used steady-state data from laboratories, past studies, and stored database from manufacturers. Some of the data are collected from quite old machines, which may perform poor on emitting. After defining the specific equipment to be estimated, these original datasets then are adjusted by adding additional factors to incorporate different conditions of that equipment into the estimation. However, Lewis used portable monitoring system to measure dynamic emissions data from job sites. In his method, the emissions are obtained based on fuel consumption. And the fuel consumption depends on attributes of the equipment, such like horsepower, duty cycle, etc. The two different calculate algorism determines the very discrepancy

between the two databases on emission factors' estimation

Table 10: The table of emission factors for each equipment

Emission Factors	EPA's Database (2004)					
	WheelLoader		Truck		Grader	
CO_2(kg/hr)	110.30		143.16		81.79	
CO(g/hr)	440.77		616.12		198.38	
HC(g/hr)	44.89		59.94		51.88	
NOx(g/hr)	1196.61		1583.09		835.63	
PM(g/hr)	63.47		107.86		74.13	
	Lewis' Database (2009)					
	WheelLoader		Truck		Grader	
	Idling	Load Truck	Idling	Hauling	Idling	Resurf-ace
CO_2(kg/hr)	6.72	40.29	6.72	27.97	6.72	56.48
CO(g/hr)	36.00	173.27	36.00	124.37	36.00	200.45
HC(g/hr)	18.34	72.35	18.34	55.06	18.34	75.52
NOx(g/hr)	105.96	510.01	105.96	373.92	105.96	655.43
PM(g/hr)	0.67	4.09	0.67	2.85	0.67	5.86

3.1.3.2   Idle, work, and total emissions

As the duration inputs of the model are distributions, the simulated emission amounts should also be uncertain values. The mean value, standard deviation, and between range in 95% confidence level for idle emissions (emissions from the idling state),work emissions (all other emissions from the working state) and total emissions (idle and work emissions together) for each air pollutant from 20 simulation runs, using both the EPA's and Lewis' databases, are displayed in Table 11.

Table 11: The data for emissions produced from 20 simulation runs of the operation

20 runs	EPA's Database			
	Mean	Std. Deviation	95% Confidence Level between	
idleCO$_2$(kg)	3890.98	96.72	3843.38	3938.58
idleCO(g)	16338.18	417.85	16132.53	16543.83
idleHC(g)	1613.68	40.56	1593.72	1633.64
idleNOx(g)	42749.96	1070.63	42223.04	43276.88
idlePM(g)	2695.81	73.84	2659.47	2732.15
workCO$_2$(kg)	145784.84	81.23	145744.86	145824.82
workCO(g)	622544.50	335.94	622379.17	622709.83
workHC(g)	61430.83	35.00	61413.61	61448.06
workNOx(g)	1609680.05	890.96	1609241.56	1610118.54
workPM(g)	109508.72	59.57	109479.40	109538.03
totalCO$_2$(kg)	149675.82	131.23	149611.23	149740.41
totalCO(g)	638882.68	549.56	638612.21	639153.15
totalHC(g)	63044.51	56.53	63016.69	63072.34
totalNOx(g)	1652430.01	1444.06	1651719.30	1653140.71
totalPM(g)	112204.53	99.37	112155.62	112253.43
20 runs	Lewis' Database (2009)			
	Mean	Std. Deviation	95% Confidence Level between	
idleCO$_2$(kg)	201.69	5.18	199.14	204.24
idleCO(g)	1079.77	27.76	1066.11	1093.43
idleHC(g)	550.07	14.14	543.11	557.03
idleNOx(g)	3178.18	81.70	3137.97	3218.39
idlePM(g)	20.17	0.52	19.91	20.42
workCO$_2$(kg)	29393.52	21.60	29382.89	29404.15
workCO(g)	129469.40	89.03	129425.59	129513.22
workHC(g)	56930.02	37.27	56911.67	56948.36
workNOx(g)	390122.80	272.67	389988.61	390257.00
workPM(g)	2999.96	2.21	2998.87	3001.05
totalCO$_2$(kg)	29595.21	25.85	29582.49	29607.93
totalCO(g)	130549.17	112.11	130493.99	130604.35
totalHC(g)	57480.09	49.17	57455.89	57504.28
totalNOx(g)	393300.98	340.45	393133.43	393468.54
totalPM(g)	3020.13	2.64	3018.83	3021.43

As shown in Table 11, the simulation results from the two database systems are quite different. The original explanation for this difference is the very different emission factors in Table 10 between two database systems.

The comparison of total emission amounts produced from this aggregate operation (mean value from 20 runs of the simulation model) between the two databases is shown in Figure 23.
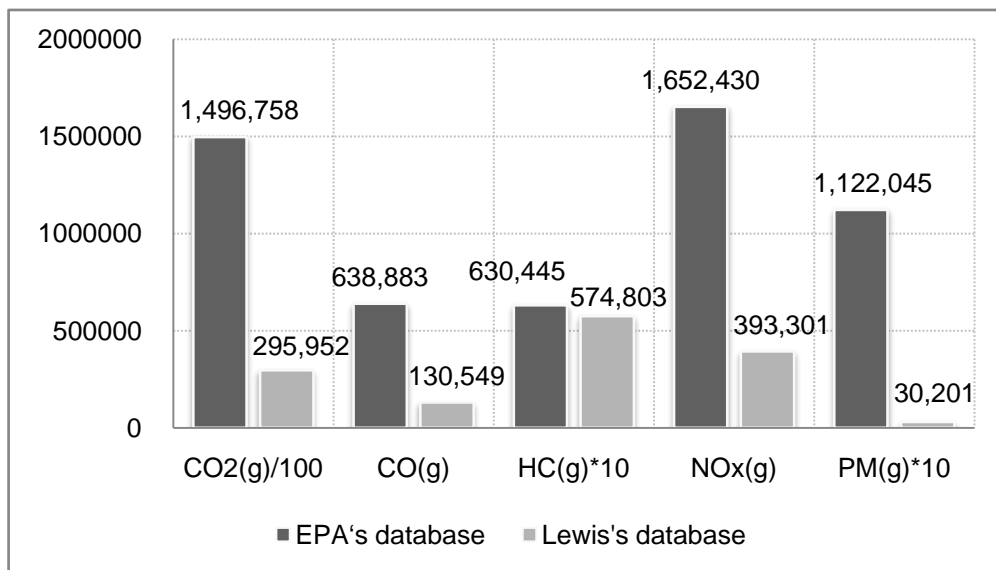
Figure 23: Total emissions from 20 simulation runs of the operation

Note:

CO_2 (g)/100: 1496758 [CO_2 (g)/100] means [149675800 g CO_2]/100

HC (g)*10: 630445 [HC (g)*10] means [63044.5 g HC] * 10

PM (g)*10: 1122045 [PM (g)*10] means [112204.5 g PM] *10

These texts on the X axis are used to ensure that the number values can be noticed clearly with the same scale on Y axis in the graph. The following graphs are applied similarly.

3.1.3.3   Daily Emissions

If we assume that the job site worked 8 hours per day, we can calculate daily emissions using this simulation model. Figure 24 shows the example of daily NOx emissions for this project on the basis of the EPA's database (either the EPA's or Lewis' database can be adopted for daily emissions analysis. Here, the EPA's database was chosen as an example and for the following analysis on scenario comparisons). From the 1st to the 5th day, the operation's daily emissions are from 287207 grams to 305894 grams of NOx. The highest NOx emissions are found on the fifth day. The last day's NOx emissions are only 155496 g because the last-day work load is approximately half the typical work load. Clearly, the daily emissions of this project have greatly exceeded the standard 85-pound (38555 gram) daily limit set by the Sacramento Metropolitan Air Quality District Management. Thus the DES model can be used to compare the estimated amount of emission with the daily limit imposed by the agency. Further, how the amount of daily emission can be reduced can be explored by adjusting resource quantity, work sequence, or equipment engines.
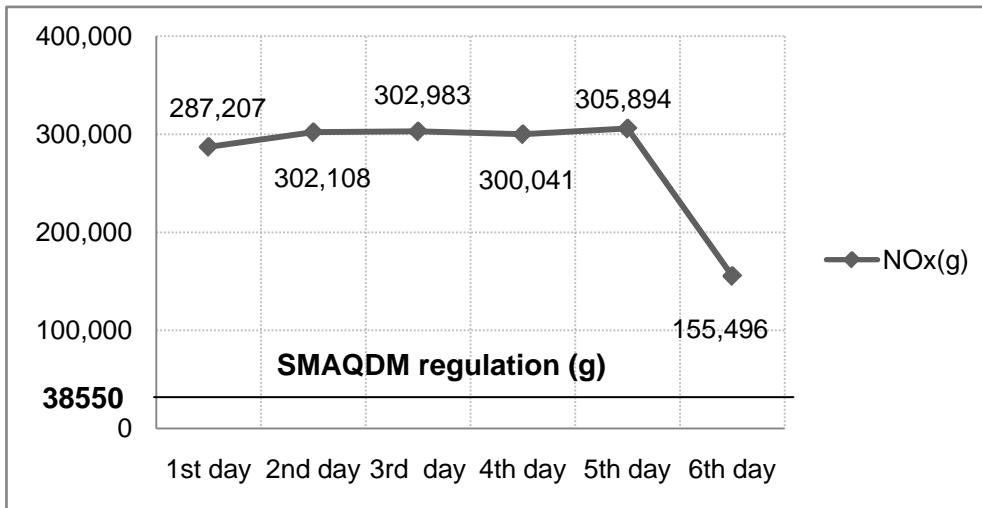
Figure 24: The graph of NOx daily emissions for the operation

3.1.3.4   Scenario Comparisons

One major benefit of this simulation methodology is the ability to compare different scenarios and to choose the optimal plan for minimal emission production. A scenario could refer to equipment allocation, work package sequence, equipment selection, etc. In this case, the equipment allocation plan (Scenario 1) uses 23 trucks, 1 loader, 1 site labor, and 1 grader to process 600 aggregate units. Table 12 shows the assumptions of four other possible scenarios, together with a project duration comparison (average value) among the scenarios after 20 model runs. The applied emission database is EPA2004.

Table 12: Possible scenario assumptions and duration outputs

	Assumptions					Duration Comparison (min)
	Aggr. Units	No.of Trucks	No.of Loader (s)	No.of Grader (s)	No. of Site Labor(s)	
Scen.1	**600**	**23**	**1**	**1**	**1**	**2668**
Scen.2	600	18	1	1	1	3366
Scen.3	600	12	1	1	1	4975
Scen.4	720	18	1	1	1	4025
Scen.5	480	12	1	1	1	3989

The average durations of scenarios 1, 2, 3, 4 and 5 are 2668, 3366, 4975, 4025, and 3989 minutes, respectively. Compared to scenario 1, scenario 2 has fewer trucks and scenario 3 has the fewest trucks. The decrease of trucks' quantity results in the longer duration. Scenario 4 is adjusted from scenario 2 by increasing aggregate units to work on, thus requires a longer duration than scenario 2. On the contrary, Scenario 5 employs the minimal work load as 480 aggregate units with the same number of trucks as scenario 3, thus the duration is reduced compared to scenario 3.

Figure 25 shows the emission data comparison for these scenarios. All the numbers in the figure are average values from 20 simulation runs. Scenario 1 is the baseline for comparison.

(a)part: Scenario 2 has higher idling emissions than scenario 1, due to a decrease in the number of trucks from 23 to 18; this greatly reduces the loader and grader

utilization rates and hence increases the total idling emissions. Scenario 3 goes to a more extreme situation with 12 trucks. This results in the worst utilization rate for equipment among these three scenarios. Scenario 3's total idling emissions thus are the highest. Scenario 1's utilization rate for equipment is the best.

(b)part: Work emissions for the three scenarios are very close. This is because the work load of 600 aggregate units remains the same. Trucks always have to finish all the aggregate units regardless of the quantity of trucks the project employs—more trucks equals fewer trips and fewer trucks equals more trips. If any scenario requires a higher work load, it will have more work emissions, depending on the size of the work load increase.

(c)part: Scenario 4 has higher idling emissions than scenario 1, due to a decrease in the number of trucks and an increase of aggregate units to work on. As discussed in the (a)part, the decreased trucks' quantity makes other equipment idle more. In addition to that, more work load means more job loops, thus making the equipment idle more as well. Scenario 5 has only 12 trucks, however, it has the lowest requirement on the work load, which offsets some of the increased idle emissions brought by the poor utilization rate. Consequently, the increase distance between scenario 4's and scenario 5's is relatively moderate compared to the distance between scenario 1's and scenario 4's.

(d)part: Scenario 4 has the maximal volume of aggregate units to finish, thus

having the most work emissions, while scenario 5 emits the least for work

emissions. As long as the work load is the same for all scenarios, their work

emissions will be very similar (discussed in (b) part).

(a) Sce.1,2,3 Idle emissions comparison (b) Sce.1,2,3 Work emissions comparison

(c) Sce.1,4,5 Idle emissions comparison (d) Sce.1,4,5 Work emissions comparison
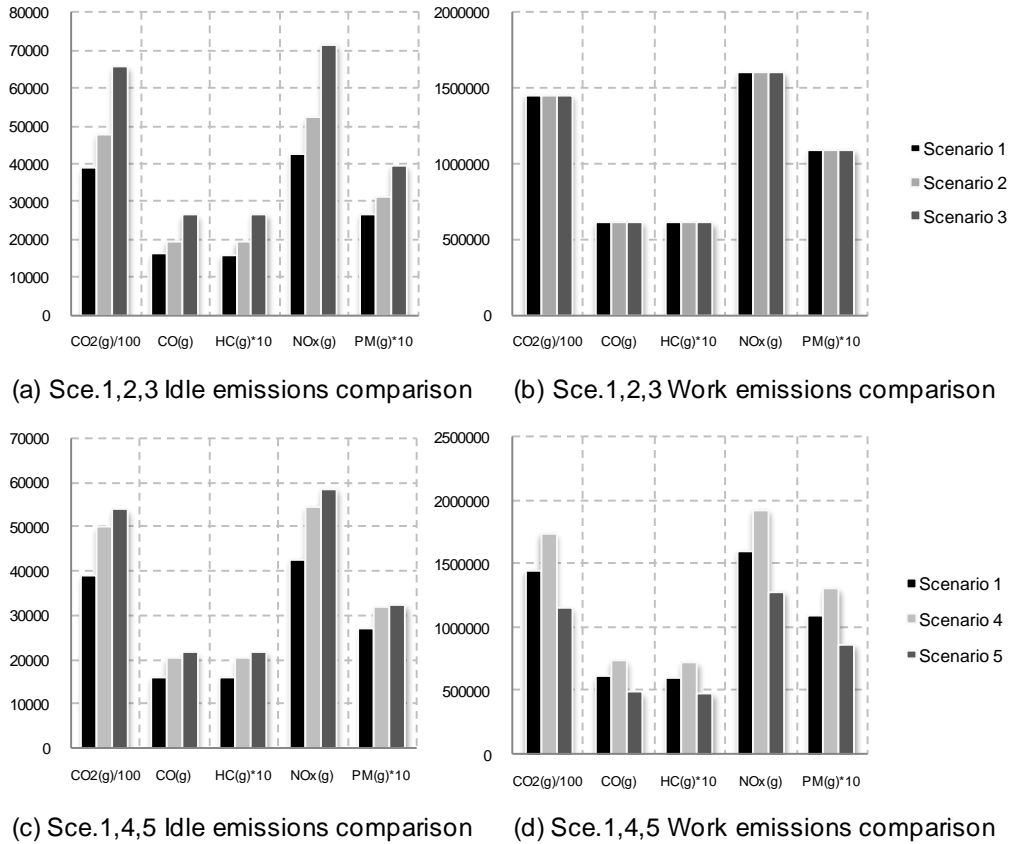
Figure 25: Comparison of emission data among scenarios

To summarize, when comparing scenarios to scenario 1:

1) Scenario 2 has 5 fewer trucks, which results in an 11.6 hour increase in project

   duration. Scenario 2 has more idling emissions (worse utilization) but the

   similar working emissions (the same work load).

2) Scenario 3 has 11 fewer trucks and the same aggregate units. The duration is 38.5 hours longer. It has the largest idling emissions (the worst utilization situation) and the similar working emissions (the same work load).

3) Scenario 4 has 5 fewer trucks and 120 more aggregate units (3600 ton), which results in a 22.6 hour increase in project duration. Scenario 4 has more idling emissions (worse utilization & more work load) and more working emissions (more work load).

4) Scenario 5 has 11 fewer trucks and 120 fewer aggregate units (3600 ton). The duration is 22.0 hours longer. It has the second largest idling emissions (the worst utilization situation but the minimal work load) and the fewest working emissions (the minimal work load).

The comparison between scenario 1, 2, 3 (a, b part) shows how the change of equipment number within the same work scope affects the emission situation; the comparison between scenario 1, 4, 5 (c, d part) demonstrates how the change of equipment number with different work scopes influences the emission situation. These scenario comparisons are simple examples that demonstrate the variation in output with different scenario inputs. The flexibility of the model enables practitioners to change parameters in the model, such as the number of site labors, number of loaders, job sequence, etc. Determining the better scenario

depends on the objectives of the project (priority of schedule acceleration or total emissions). Because of the limited scope of this article, issues of equipment cost have not been discussed. Introducing cost concerns into the scenario comparison would make this simulation-based method more comprehensive.

3.1.3.5   Case Study Summary

This case study shows the advantages of the SPS tool in the DES method. It can forecast accurate durations, emissions from idling and working, daily emissions, and emissions from various scenarios by applying different databases of emission factors.

As demonstrated, scenario comparisons are simple to set up with the SPS method. Aside from the scenario types which were discussed in this case study (e.g., job size, number of trucks), other possible scenarios, such as using newer equipment with fewer emissions or attaching new duty cycles, also can be achieved easily by changing the parameters of the simulation model.

3.2 Regina earthmoving case study[3]

The previous case study of an aggregate project shows the basic modeling process and the merits of the DES application on estimating emissions. However, this case study of an earthmoving project in Regina (Ahn et al. 2010b) focuses on the differences between the DES and traditional methods. The DES method refers to building a DES model based on either Lewis' or the EPA's database, while the traditional method applies the EPA's database to get emissions by manually multiplying the emission factors from the database with roughly estimated durations.

3.2.1 Project background

Consumers' Co-operative Refineries Ltd. (CCRL) had a project for installing tank farms in Regina, SK, Canada. This project contained some earthmoving tasks, one of which was selected as this case study. The chosen task (code 10 earthwork) aimed to strip existing topsoil (23095 cubic yard) that averaged 6 inches in thickness from arable farmland and to store the soil in designated locations (within a 1 mile haul distance) on site. Table 13 presents the durations

---

[3] Two versions of this section have been published: Enhanced estimation of air emissions from construction operations based on discrete-event simulation in "The International Conference on Computing in Civil and Building Engineering (ICCCBE) 2010," Nottingham, U.K., June 30-July 2 2010 and Lessons Learned from Applying DES for Emission Estimating in "2010 Winter Simulation Conference Integration & Collaboration," Baltimore, Maryland, U.S., December 5 ~ 8, 2010.

and equipment details to get emission outputs. The contractor for the project also

provided necessary data for simulation, such as equipment production rates, soil

quantity, etc.

Table 13: Equipment attributes and durations for each duty cycle in this case study

Equipment type	Equipment quantity	Horsepower	Model year [1]	Duty cycle (duration/cycle[2])	
CAT D9T Bulldozer	2	410 hp	2005	Rough Grade (2.6 min)	Stock Pile (2.6 min)
CAT 740 Off-Road Truck	6	469 hp	2002	Haul Soil (5 min for loaded haul, 2.2 min for empty haul, and 1.5 min for dump)	
HIT EX 750 Excavator	1	453 hp	1999	Excavate Soil (2.9 min)	
CAT 14M Grader	1	259 hp	2004	Resurface (0.6 min)	

Note:
1. The model years of each piece of equipment are assumed based on the
   equipment model.
2. The duration per cycle refers to mean values, as provided by the contractor.

Figure 26 displays the operation process and equipment involvement for this

stripping topsoil task.

To reflect the construction projects' uncertainty, distributions are adopted to

represent durations of each duty cycle. Beta distribution generally is

recommended for inputting the random data of construction durations for
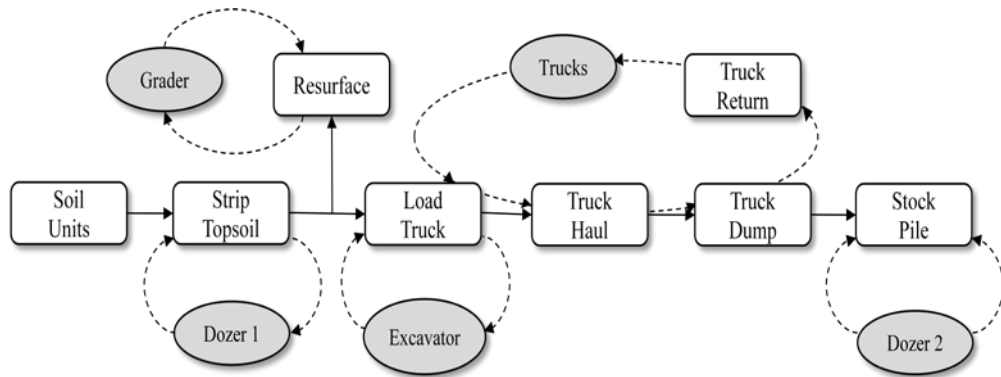
Figure 26: The stripping topsoil task's operation flow map

simulations (AbouRizk and Halpin 1992). Normal distribution is especially suitable,

however, for representing the duration data of truck haul and return duty cycles

(Martinez et al. 1994). In this case study, normal distribution thus is taken to define

the durations of truck haul and return duty cycles, while beta distribution is used to

define other durations. Based on the mean value data provided by the contractor

in Table 13, proper distribution parameters are assumed (Martinez et al. 1994)

(Table 14).

Table 14: The assumed distributions for each duty cycle

Equipment type	Duty cycle	Distribution of duration(min)
CAT D9T Bulldozer	Rough Grade (striptopsoil)	Beta(1.8, 4.2, 1.7, 6.2)
	Stock Pile	Beta (1.8, 4.2, 1.7, 6.2)
CAT 740 Off-Road Truck	Haul Soil (haul)	Normal (5, 1.25)
	Haul Soil (return)	Normal (2.2, 0.33)
	Haul Soil (dump)	Beta (1.77, 4.23, 1, 3.6)
HIT EX 750 Excavator	Excavate Soil (loadtruck)	Beta (1.78, 4.22, 1.9, 7)
CAT 14M Grader	Resurface	Beta (2.65, 3.35, 0.04, 1.4)

3.2.2 DES Method

Figure 27 shows the built model's outlook in the Simphony.
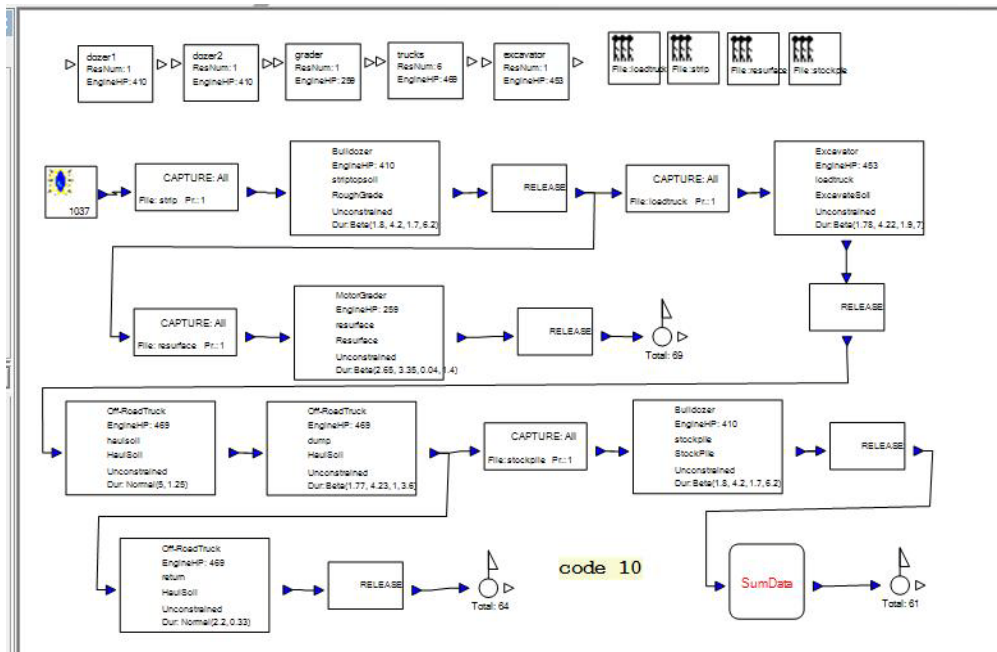
Figure 27: The Simphony model of the stripping topsoil task

Based on the equipment's attributes, emission factors can be generated. Table 15 presents the emission factors of each duty cycle in Lewis' database. All types of equipment have the same emission factors when idling, as indicated in the algorism of Lewis' database. This is because Lewis defines mode 1 as an idling cycle (section 2.2.2) and all types of equipment are assumed to be running in mode 1 while idling. Table 16 shows the emission factors in the EPA's database.

Figure 28 interprets the data from Tables 15 and 16 into graphics (in Lewis' database, the average value is taken from two different duty cycles to represent

dozer emission factors). Basically, the EPA's emission factors (especially PM emission factors) are larger than Lewis', except for HC, CO, and NOx emission factors for the grader. The reasons for the emission factor deviations already have been explained in the aggregate project case study.

Table 15: The emission factors of each duty cycle based on Lewis' database

Equipment type	Duty cycle	Emission factors				
		CO_2 (kg/hr)	CO (g/hr)	HC (g/hr)	NOx (g/hr)	PM (g/hr)
Bulldozer	Rough Grade	55.13	270.01	**130.09**	806.53	5.56
	Stock Pile	<u>83.44</u>	<u>272.45</u>	100.53	<u>962.29</u>	<u>8.78</u>
Truck	Haul Soil	28.84	128.26	56.78	385.64	2.94
Excavator	Excavate Soil	**98.05**	**341.57**	<u>126.94</u>	**1122.52**	**10.22**
Grader	Resurface	56.48	200.45	75.52	655.43	5.86
All equipment	Idle	6.72	36.00	18.34	105.96	0.67

Note:
Bold: the highest value in the column; Underline: the 2nd highest value in the column.

Table 16: The emission factors based on the EPA's database

Equip.	Emission factors (load factor included)				
	CO_2 (kg/hr)	CO (g/hr)	HC (g/hr)	NOx (g/hr)	PM (g/hr)
Bulldozer	129.61	324.23	42.96	999.76	41.34
Truck	**148.25**	<u>396.55</u>	50.32	<u>1150.94</u>	<u>62.38</u>
Excavator	<u>143.16</u>	**588.66**	**58.90**	**1564.44**	**91.97**
Grader	81.80	187.64	<u>50.73</u>	584.49	30.04

Note:
Bold: the highest value in the column; Underline: the 2nd highest value in the column.
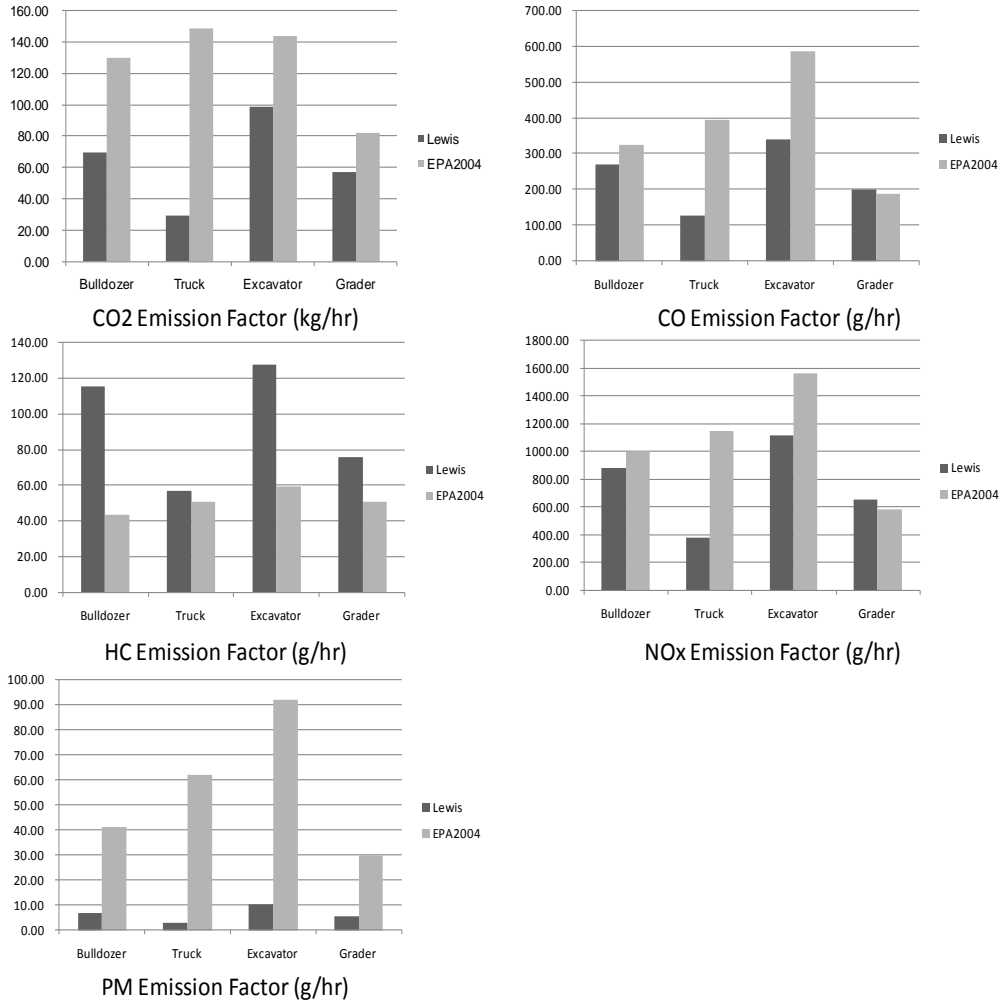
Figure 28: Emission factor deviations for each piece of equipment, derived from the two methods

Table 17 shows the accumulative durations (average values) of each type of equipment simulated and Table 18 shows the average values of emission amounts, based on Lewis' and the EPA's databases, respectively, after 20 simulation model runs. The average values from using EPA's database will be compared with the emission amounts obtained from traditional methods in the 3.2.4 section. A brief summary of the emission amounts finds that, according to

Lewis' standard, the stripping topsoil task emits more than 19 tonnes of CO_2, 77

kg of CO, 32 kg of HC, 246 kg of NOx, and 2 kg of PM. The emission intensity

(emission rate per soil unit) of CO_2 is 0.8 kg/cubic yard. The two bulldozers emit

the most and the trucks produce the second largest share of CO, HC, and NOx

emissions. According to the EPA's database, this task generates more than 72

tonnes of CO_2, 202 kg of CO, 26 kg of HC, 587 kg of NOx, and 30 kg of PM. The

emission intensity of CO_2 is 3.0 kg/cubic yard. Differing from Lewis' database, the

EPA's database determines the truck to be the biggest emission contributor and

the dozer to be the second major pollution source in nearly all air pollutants,

except for PM.

The obvious result differences between the two databases are due to different

emission factors.

Table 17: The simulated total durations in the DES method

Equip.	Total Durations (hr)
Bulldozer	111.66
Truck	297.18
Excavator	59.43
Grader	59.33

Table 18: The average values of emission amounts in the DES method

Equip.	Emission amounts (Lewis' database)				
	CO₂ (kg)	CO (g)	HC (g)	NOx (g)	PM (g)
Bulldozer	**7335.80**	**28765.51**	**12253.97**	**93760.70**	**759.03**
Truck	5427.63	<u>24996.70</u>	<u>11405.39</u>	<u>74832.38</u>	551.81
Excavator	<u>5806.06</u>	20227.95	7517.60	66474.60	<u>605.47</u>
Grader	907.02	3726.40	1603.71	11693.33	93.01
Total	*19476.51*	*77716.56*	*32780.69*	*246761.01*	*2009.31*
	Emission amounts (EPA's database)				
Bulldozer	<u>15422.00</u>	<u>38581.27</u>	<u>5111.87</u>	<u>118962.58</u>	4919.51
Truck	**43879.20**	**117367.70**	**14892.30**	**340646.34**	**18462.36**
Excavator	8520.03	35032.96	3505.27	93103.72	<u>5473.30</u>
Grader	4887.46	11211.80	3030.94	34923.40	1794.85
Total	*72708.69*	*202193.73*	*26540.39*	*587636.05*	*30650.01*

Note:

Bold: the highest value for all equipment; Underline: the 2nd highest value for all equipment.

3.2.3 Traditional Method

The traditional method uses the EPA's database as the algorism to get the emission factors. Practitioners have to check the EPA's database document and manually match the emission factors according to the equipment's attributes. The total duration data of involved equipment is estimated by contractors based on experiential calculation. The emission output then is obtained by manually multiplying emission factors with durations. The previous section already has shown the EPA's emission factors. Table 19 shows the manually estimated

durations; Table 20 shows the calculated emission amounts.

Table 19: The estimated durations in the traditional method

Equip.	Total Durations (hr)
Bulldozer	88.83
Truck	266.48
Excavator	44.41
Grader	11.10

Note:
Bold: the highest value for all equipment; Underline: the 2nd highest value for all equipment.

Table 20: The manually calculated emission amounts in the traditional method

Equip.	Emission amounts				
	CO_2(kg)	CO(g)	HC(g)	NOx(g)	PM(g)
Bulldozer	11513.26	28801.35	3816.14	88808.68	3672.23
Truck	**39505.66**	**105672.64**	**13409.27**	**306702.49**	**16623.02**
Excavator	6357.74	26142.39	2615.75	69476.78	4084.39
Grader	907.98	2082.80	563.10	6487.84	333.44
Total	58284.63	162699.19	20404.26	471475.79	24713.09

Note:
Bold: the highest value for all equipment; Underline: the 2nd highest value for all equipment.

In this method, this job task produces more than 58 tonnes of CO_2, 162 kg of CO, 20 kg of HC, 471 kg of NOx, and 24 kg of PM. This is quite different from the DES method's output that utilizes the same EPA emission factor database. The

difference will be discussed further in the next section. In this method, however, the trucks emit the most of all equipment and the bulldozers produce the second largest share of CO, CO_2, HC, and NOx emissions.

3.2.4 Comparison between the DES and traditional methods

Comparisons focus on the difference in estimated durations and emission amounts between the two methods. The DES method selects the EPA's database to run the simulation for comparison; it thus is meaningful to compare the DES's emission amounts with those from the traditional method, which also uses the EPA's database.

The deviation of total accumulated duration (hrs) data (Table 17, Table 19) between the two methods is described as a graph in Figure 29. The duration data obtained from the DES (average value from 20 runs) also includes the time spent in the idling state. This explains why the DES's simulated durations are always longer than the traditional method's results. For example, the grader is idling most of the time (around 40 hrs) because its duty cycle closely follows the dozer's rough grade duty cycle. However, the mean value (0.6 min) of the duration of the grader's duty cycle is far less than that (2.6 min) of the dozer's duty cycle. Thus, each time the grader has to wait until the dozer finishes its job. However, the

experiential estimation of the traditional method does not consider this idle time. This is the big difference between grader duration estimations from the two methods. The DES duration estimation is more accurate, especially when the analyzed project is large.
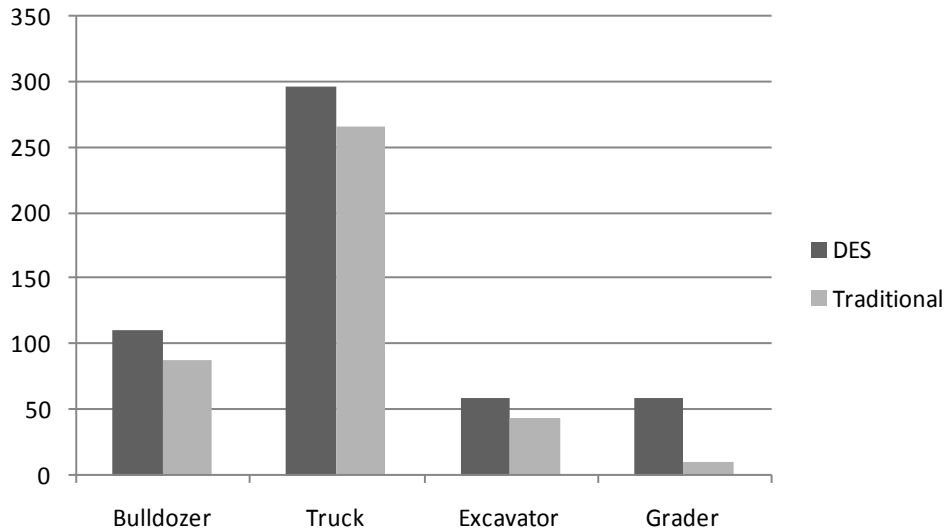
Figure 29: Deviations of the total accumulative durations for each piece of equipment derived from the two methods

Figure 30 provides the air-pollutant-specific outputs for emission amounts. It reveals that the DES method generates larger values for emission amounts (all the data in DES method in this figure are the average values from 20 runs). The discrepancy is caused by two factors: duration and utilization rate.

Because of idling, the durations estimated by the DES method are longer; this is the key reason for greater DES emission estimates with the same emission factor

database. The utilization rate, which is considered in the DES method, affects the extent of the difference between the two methods. For example, the utilization rate of the grader in the DES method is the lowest of all equipment. It is 20.6%, which means the grader is idling (waiting for the dozer) most of the time. Idling emissions thus dominate emissions for the grader. This is not considered in the traditional method. As Figure 29 displays, the difference extent for the grader's emissions between the two methods is much greater than for other types of equipment.

In conclusion, the computer-based duration and utilization rate estimates of the DES method make it more accurate for emission estimation. This is because the DES attempts to duplicate the real conditions of projects.
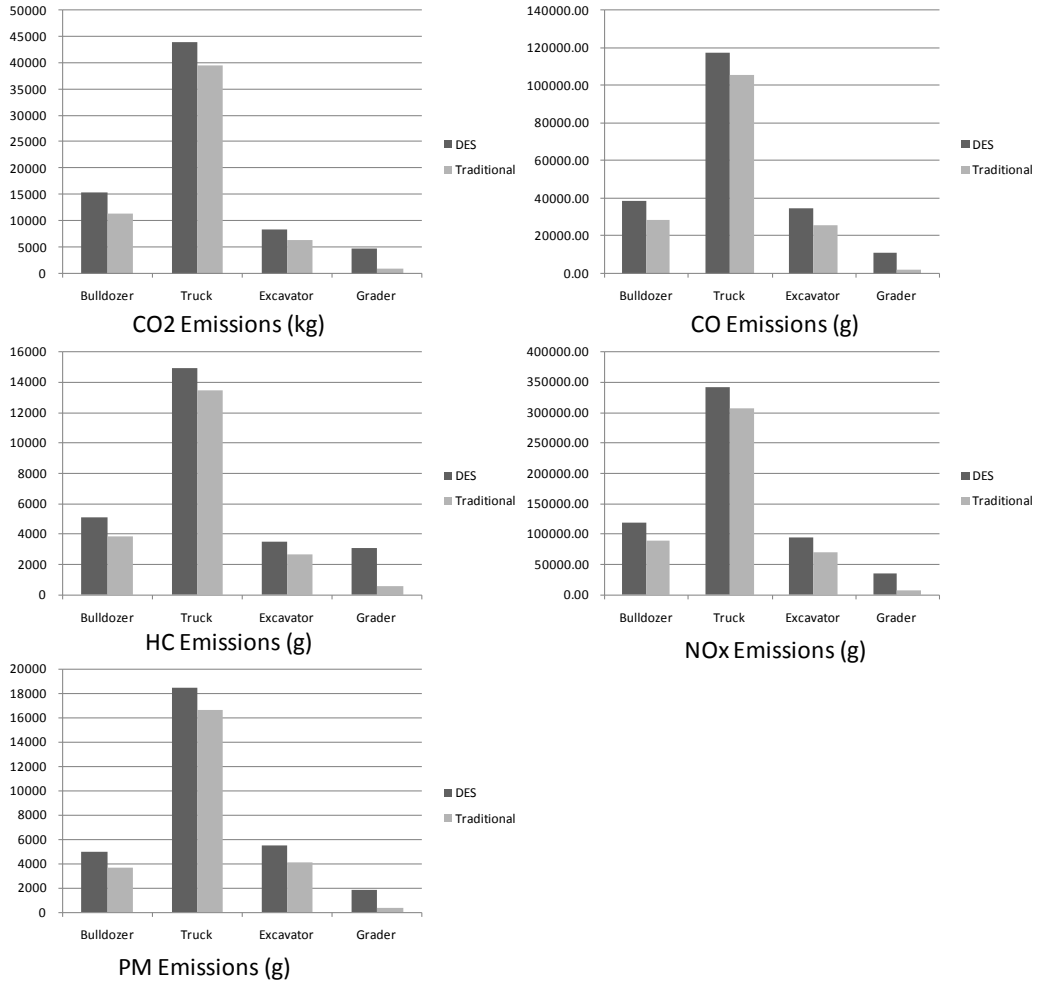
Figure 30: Emission amount deviations between pieces of equipment in the two methods

Chapter 4: HLA (Emission federate)

While the SPS allows a DES simulation of emission output without any programming knowledge, it still needs a model which is constructed to accurately reflect the job operation. If there is a special emission component, which can work together with other components (e.g., the operation component or productivity component) within a simulation system, it will save a lot of effort.

4.1 Description of concepts

High Level Architecture (HLA) defines a software architecture which allows simulation applications to be built by combining other simulation components. The components, which are called federates, are individual simulations. A federation refers to an assembly of multiple federates which are designed for a common object or project (e.g., a "CraneLiftingProject" federation may contain an operation, LiftScenario, visualization, and emission federate.). Federates also can be hooked up to other federations beyond the federation for which they were originally designed. The runtime infrastructure (RTI) is responsible for the interaction and data delivery process between federates (Kuhl et al. 1999).

The Construction Synthetic Environment (COSYE) is a HLA-standard software

79

environment designed by the University of Alberta for the purpose of building large-scale construction simulations. The COSYE contains a COSYE RTI server, a COSYE federate host, a COSYE framework, Simphony Core Services, etc. Users can build a HLA simulation model through Microsoft Visual Studio 2008 or Simphony, in which the COSYE is embedded (AbouRizk and Hague 2009).

In this research, the designed COSYE emission federate is the emission component. The emission federate communicates with other federates, permitting users to link the emission federate with other federates and to run the set of federates in the same federation. Users thereby only need to concern themselves with the emission federate, rather than worry about building models that reflect operations; this will be taken care of by other federates.

4.2 Framework

Figure 31 describes how the HLA simulation works. The simulation contains two federates: the operation federate is responsible for publishing equipment attributes and parameters; the emission federate gives emission-relevant outputs. The task of building the internal code of the operation federate is not within the scope of this research and thus a simple Simphony.NET 3.5 model is adopted to represent the operation federate. This is created by simply drawing visible

COYSE modeling elements instead of coding. The Simphony model is not able to show what the operation looks like, but provides outputs of equipment ID, equipment horsepower, duration, etc., all of which are assumed (these outputs are supposed to be simulated instead of assumed if any operation federates are available in the future). These outputs are needed by the emission federate to calculate emissions. The RTI can convey these outputs into the Visual-Studio-2008-based emission federate, which subsequently analyzes them and generates emission outputs. The two emission databases, EPA 2004 and Lewis', are applied in the emission federate.
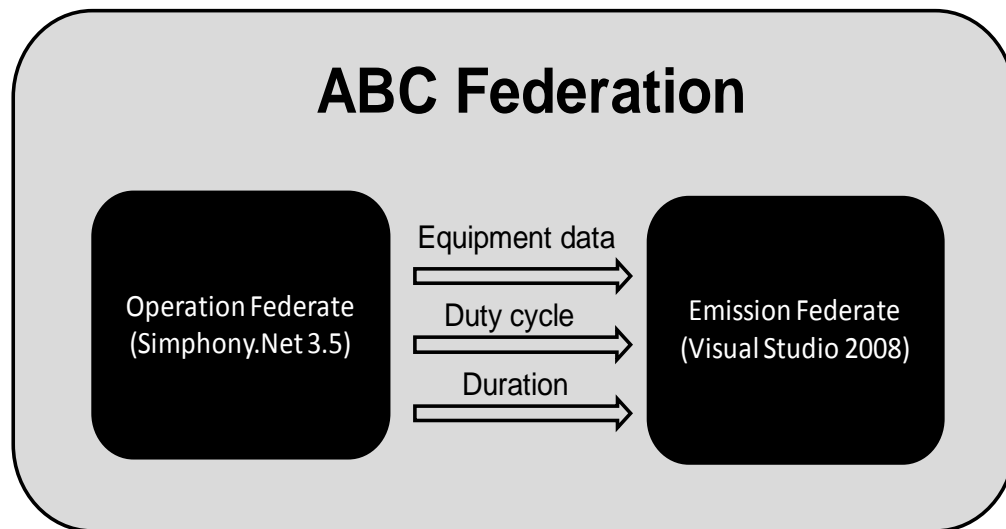

Figure 31: The framework of HLA federate methodology

4.3 Simulation

4.3.1 The Simphony model

The Simphony model represents a rough-version operation federate. It creates pieces of equipment and declares their parameters. The parameters include equipment ID, equipment type, equipment horsepower, equipment model year, equipment duty cycle, and total work time (duration) of equipment.

For example, a project involves 1 crane, 1 excavator, and 1 truck. Table 21 shows their assumed attributes and the work time for each duty cycle (the crane is not assigned to any duty cycle because Lewis' database excludes cranes).

Table 21: Assumptions for equipment

Equipment type	Equipment ID	Horsepower	Model year	Duty cycle (total duration)	
Crane	1	320	2003	N/A (1600min)	
Excavator	2	300	2008	Move Rock (2400min)	Excavate Soil (2300min)
Truck	3	350	2006	Haul Soil (3800min)	

Figure 32 displays this Simphony.NET 3.5 model. The three register elements represent the three created pieces of equipment and their parameters, while the update element is used to update information for another duty cycle of the excavator.
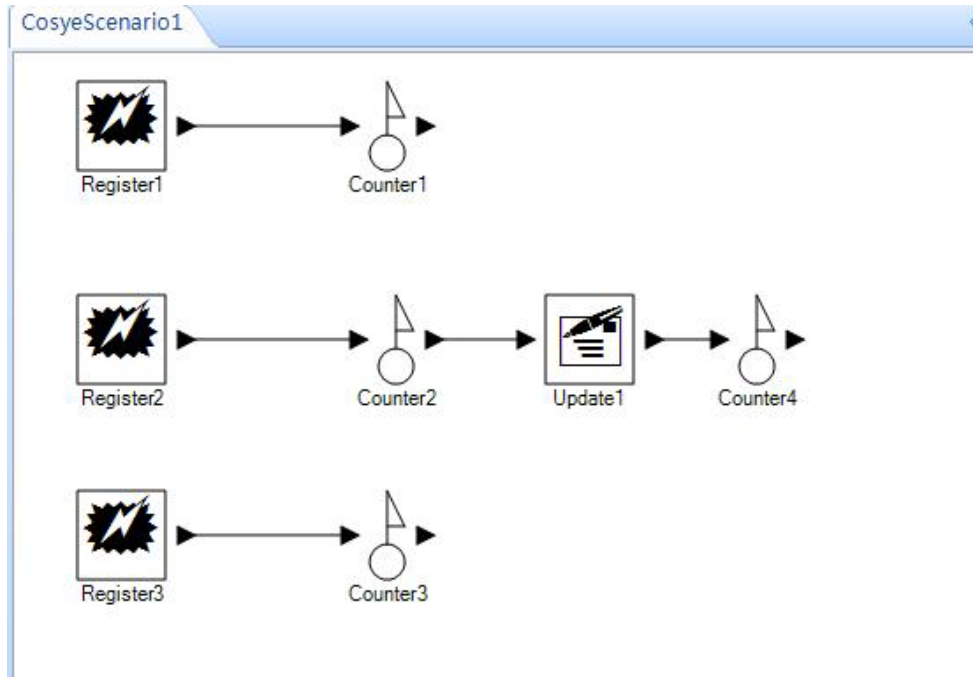
Figure 32: The Simphony.NET 3.5 model's outlook

Figure 33 shows the input window of the register element, in which the parameters can be modified.
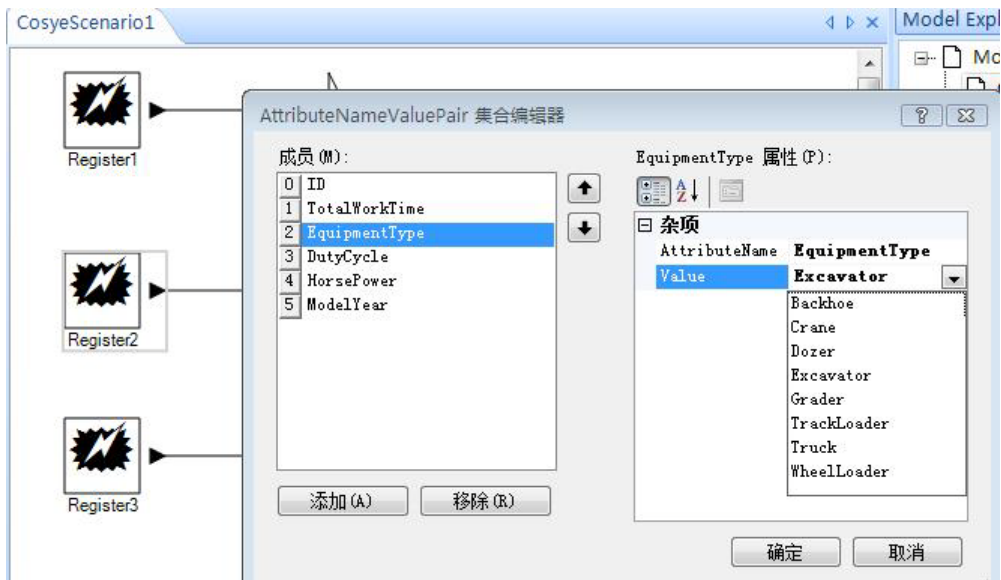
Figure 33: The user input interface of the register element (Register2: Excavator)

Again, it should be mentioned that this Simphony model is only for temporary use

and is to be employed until a designed comprehensive operation federate, which

can model the actual operation, is able to replace it.

4.3.2   The emission federate

The emission federate (Figure 34) reflects information published from the

Simphony model and then calculates the emission factors and emission amounts

(CO_2, CO, NOx, PM, and HC).

Figure 34: The user interface of the emission federate

A brief explanation of this interface follows (from top to bottom):

1) The top four lines illustrate the basic settings of the federate. Users only need

to ensure that the federation name (emissions) is consistent with the one in the Simphony model, so that they can work in the same federation.

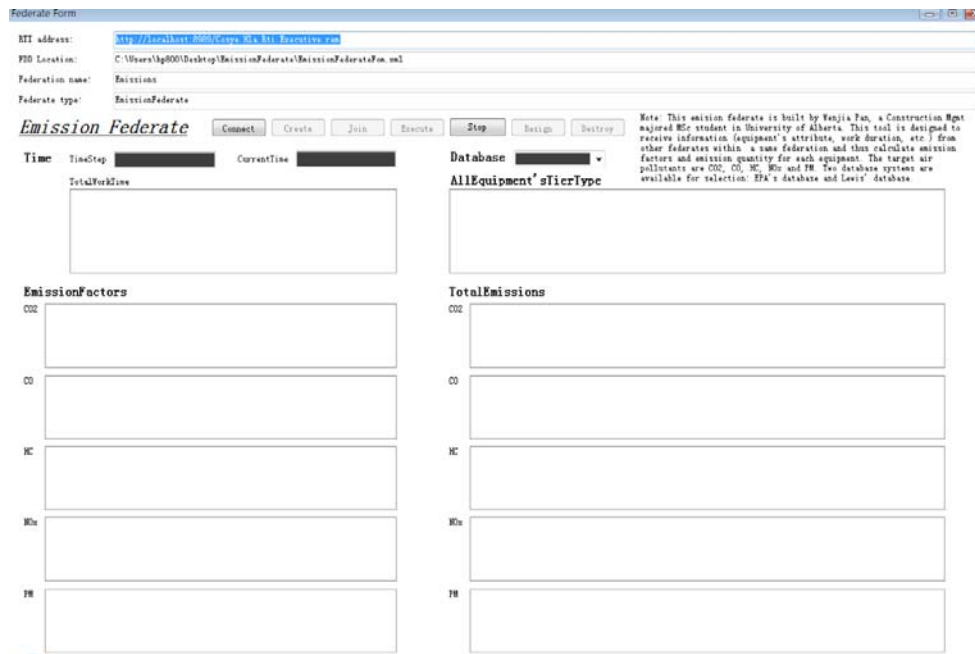2) The operation buttons (connect, create, join, execute, stop, resign, and destroy) are used when running the HLA. They will be explained further in the next section.

3) The time area includes TimeStep, CurrentTime, and TotalWorkTime. The TimeStep textbox shows the time interval of the timer tick. The CurrentTime shows the current running time. They are not important for the estimation of emissions. The TotalWorkTime listbox lists all the duration information for each duty cycle of equipment.

4) The Database combobox provides available emission factors databases to be selected.

5) The AllEquipment'sTierType listbox shows all the tier type information of equipment.

6) The EmissionFactors area compiles the five air pollutants' emission factors from each duty cycle.

7) The TotalEmissions area lists the five air polluntants' total emissions from each duty cycle.

4.3.3 Simulation

Before running the simulation, users should make certain whether the FederationName is the same in both the Simphony model and the emission federate. In addition, the Coyse RTI service manager should be started. The steps to run and stop the simulation are:

Step 1: click run for both models

Step 2: click the connect and join button in the emission federate

Step 3: press OK in the message box (click OK when all federates have joined the federation) in the Simphony model

Step 4: select one emission factor database in the emission federate

Step 5: click the execute button in the federate (it will show the emission outputs instantly in the federate interface, with the current time changing forward)

Step 6: stop the simulation by pressing the stop button in the federate

Step 7: click resign and then destroy in the federate to exit the simulation

Step 8: click OK in the message box (simulation completed) in the Simphony model
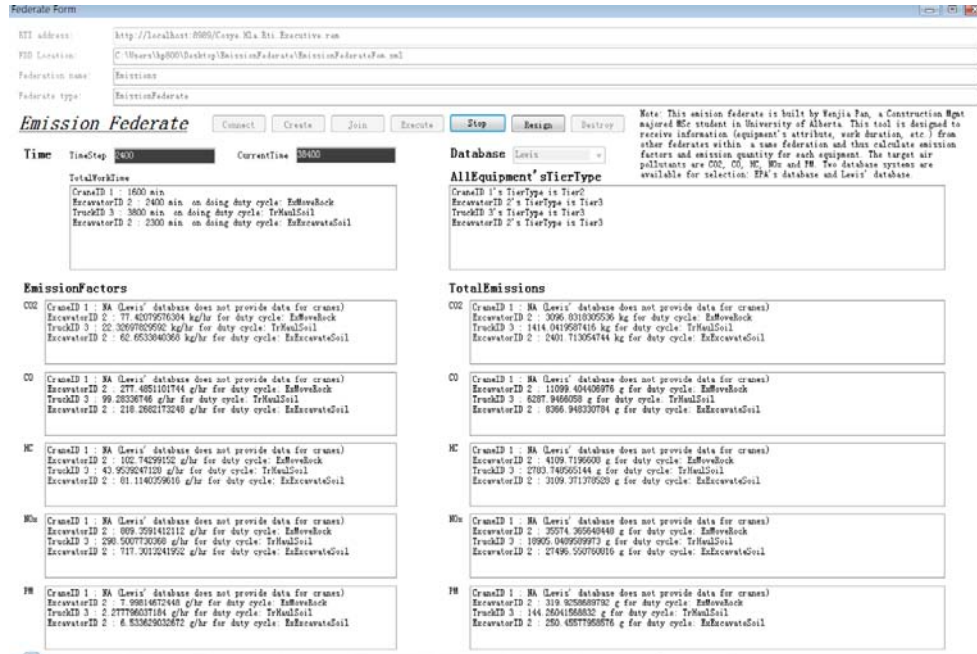
Figure 35: The final outputs of the emission federate

In this simulation run (Figure 35), the Lewis' emission factor database was selected. According to the information sent from the Simphony model, the emission federate determines the tier type for each piece of equipment. The internal emission-calculation algorism then provides the emission factors and total emissions (e.g., the truck has a CO_2 emission factor of 22.33 kg/hr and CO_2 total emissions of 1414.04 kg for the HaulSoil duty cycle). The crane does not have data output for emission factors and total emissions because Lewis' database does not include data for cranes.

It can be concluded from the HLA simulation that the knowledge and effort of users regarding the operation of a simulation have been minimized. However, the

other federates which can be hooked to this emission federate in the same

federation continue to be less developed and tested.

Chapter 5: Conclusion

5.1 Contributions

The contributions of this research can be summarized in the following aspects:

1) The DES method is different from other macro models, some of which are likely to overestimate emissions because equipment is considered to be working all the time during the project; others may underestimate emissions because they do not consider idle time. This method is capable of estimating emissions from individual project-specific construction processes. In this way, it is a micro-estimating tool, which has been lacking until now.

2) As long as there is a widely-accepted and various duty-cycle (including idling)-based emission factors database for most construction equipment, the DES tool can provide more accurate, practical, and reliable emission estimation. This is because the simulation simulates what will really happen, including equipment idling time.

3) The DES tool can be used in the pre-planning stage for estimation and scenario comparisons. It is very flexible and friendly to operate. Users can see how the emissions change by easily modifying the attribute inputs, working sequences, and quantity. This makes optimal decisions on environmental sustainability easier to form. The DES tool can be very reliable for initial

decision making.

4) The DES method considers equipment's utilization rate as a factor affecting emissions. It is also able to measure emissions for different identified states of equipment (various duty cycles, or idle state) and thus the estimating process more realistic and reliable.

5) The HLA federate method provides a new conception of the emission component in a simulation network. The emission component will be the only concern for users and thus models' building are no longer required. This will inspire future research that is relevant to simulation and emission estimation.

5.2 Limits

Although this DES methodology presents several advantages which can fill gaps in the functionality of current estimating tools, there are still challenges. First, the method needs an accurate and extensive emission factor database which covers as much construction equipment as possible and differentiates emission factors for equipment duty cycles. The simulation also demands accurate and detailed data input collections, such as reasonable distribution assumptions for duty cycle durations. If the emission factors are not available, emission factor collection experiments may be needed to get factors from equipment on the job site. This data collection will require a number of observations and additional equipment.

As for the HLA federate method, it makes simulation easier but relies too much on data imported from other federates. It therefore has a high dependence on other federates, which must provide detailed and accurate duration data for each piece of equipment and specific duty cycles. However, these types of federates remain less developed.

5.3 Summary

Simphony's SPS makes it possible for practitioners to utilize easily DES to correctly estimate the environmental effects of construction equipment. A validation framework was also introduced for testing the reliability of the DES tool. The HLA federate is easier for practitioners to utilize simulation tools, so long as other federates within the same federation export reliable data.

Both the SPS-based DES and HLA federate are new and developing simulation approaches. They remain imperfect and need more discussion. However, with their unique functionality with regard to the estimation of micro-level emissions, the simulation method, together with other macro-level estimating tools, will comprise a fairly comprehensive system to estimate gas emissions from construction equipment reliably.

REFERENCES AND BIBLIOGRAPHY

AbouRizk, S.M., and Hague, S. 2009. An Overview of the Coyse Environment for Construction Simulation. *In* Proceedings of the 2009 Winter Simulation Conference*,* Austin, Texas, U.S., 13-16 December 2009. pp. 2624-2634.

AbouRizk, S.M., and HALPIN, D.W. 1992. Statistical Properties of Construction Duration Data. Journal of Construction Engineering and Management, 118(3): 525-544.

AbouRizk, S.M., and Hajjar, D. 1998. A Framework for Applying Simulation in the Construction Industry. Canadian Journal of Civil Engineering*,* 25(3): 604-617.

Ahn, C., Lee, S.H., Pena-Mora, F., and S. Abourizk. 2010a. Toward environmentally sustainable construction processes: The U.S. and Canada's perspective on energy consumption and GHG/CAP emissions. Sustainability, 2(1): 354-370.

Ahn, C., Pan, W., Lee, S.H., and Pena-Mora, F. 2010b. Enhanced estimation of air emissions from construction operations based on discrete-event simulation, *In* Proceedings of the International Conference on Computing in Civil and Building Engineering (ICCCBE) 2010, Nottingham, U.K., June 30-July 2 2010. International Society for Computing in Civil and Building Engineering.

Ahn, C., Xie, H., Lee, S.H., AbouRizk, S.M., and Pena-Mora, F. 2010c. Carbon Footprints Analysis for Tunnel Construction Processes in the Preplanning

Phase Using Collaborative Simulation. *In* Proceedings of the Construction Research Congress 2010, Banff, Alberta, Canada., 5-8 May 2010. American Society of Civil Engineers. New York, pp. 1538-1546

California Air Resource Board (CARB). 2006a. Overview: OFFROAD Model. Available from http://www.arb.ca.gov/msei/offroad/pubs/offroad_overview.pdf [cited 5 November 2009]

California Air Resource Board (CARB). 2006b. EMFAC2007 version 2.30 Calculating emission inventories for vehicles in California, User's Guide. Available from http://www.arb.ca.gov/msei/onroad/latest_version.htm. [cited 5 November 2009]

Caterpillar. 2010. Articulated Trucks. Available from http://www.cat.com/equipment/articulated-trucks. [cited 26 May 2010]

Farrar, J.M. 2003. Development of a Lean Approach in Simulation Using Surface Works Operations of Road Construction. M.Sc. thesis, Department of Civil and Environmental Engineering, The University of Alberta, Edmonton, AB, Canada.

Guggemos, A, A.; Horvath, A. 2006. Decision-Support Tool for Assessing the Environmental Effects of Constructing Commercial Buildings. Journal of Architecture Engineering, 12(4): 187-195.

Hajjar, D. and AbouRizk, S.M. 1999. Simphony: an environment for building special purpose construction simulation tools. *In* Proceedings of the 1999 Winter Simulation Conference, Phoenix, Ariz., 5-8 December 1999. pp. 998-1006

International Organization for Standardization (ISO). 1997. Environmental management - Life cycle assessment - Principles and framework. International Standard 14040, ISO, Geneva, Switzerland.

Kuhl, F., Weatherly, R., and Dahmann, J. 1999. Chapter 3: An Overview of the HLA. *In* Creating Computer Simulation Systems: An Introduction to the High Level Architecture. *Edited by* Kathleen M. Caren. Prentice Hall, Inc Upper Saddle River, NJ, U.S. pp. 19.

Lewis, M.P., 2009. Estimating Fuel Use and Emission Rates of Nonroad Diesel Construction Equipment Performing Representative Duty Cycles. Ph.D. thesis, Department of Civil Engineering, The North Carolina State University, Raleigh, NC, U.S.

Martinez, J.C., Ioannou, P.G., and CARR, R.I. 1994. State and Resource Based Construction Process Simulation. *In* Proceedings of the First Congress on Computing in Civil Engineering, Washington, D.C., 20-22 June 1994. American Society of Civil Engineers, New York, pp. 177-184

Pena-Mora, F., Ahn, C., Golparvar-Fard, M., Hajibabai, L., Shiftehfar, S., An, S., and Aziz, Z. 2008. A Framework for Managing Emissions from Construction Processes. Journal of Construction Engineering and Management, 130(3): 330-336.

R&D Chemicals. 2009. Search results for Chess Fine Chemicals: 344 compound(s) found. Available from

http://www.rdchemicals.com/chemicals.php?mode=searchname&searchtext=chess+fine+chemicals&pagp=4 [cited 8 June 2010].

Sacramento Metropolitan Air Quality Management District (SMAQMD), 2009a. AQMD Recommended Mmitigation for Reducing Emissions from Heavy-duty Construction Vehicles. Available from: http://www.airquality.org/ceqa/mitigation.shtml [cited 16 Apr 2010].

Sacramento Meetropolitan Air Quality Management District (SMAQMD), 2009b. Roadway Construction Emissions Model (version 6.3.2). Available from http://www.airquality.org/ceqa/RoadConstructionModelVer6.3-2.xls [cited 3 May 2010].

Sharrard, A.L., Matthews, H.S., and Roth, M., 2007. Environmental Implications of Construction Site Energy Use and Electricity Generation. Journal of Construction Engineering and Management, 133(11): pp. 846-854.

The Institute of Electrical and Electronics Engineers, Inc. (IEEE), 2010. IEEE Standard 1516: Modeling and Simulation (M&S) High Level Architecture (HLA)-Framework and Rules. March 25, 2010.

U.S. Environmental Protection Agency (US EPA), 2004a. Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling--Compression-Ignition. Technical report EPA420-P04-009, Report No. NR-009C, Assessment and Standards Division, Office of Transportation and Air Quality, United States Environmental Protection Agency, Washington D.C, U.S.

U.S. ENVIRONMENTAL PROTECTION AGENCY (US EPA). 2004b. Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling. Technical report EPA420-P-04-005, Report No.NR-005c, Assessment and Standards Division, Office of Transportation and Air Quality, United States Environmental Protection Agency, Washington D.C, U.S.

U.S. ENVIRONMENTAL PROTECTION AGENCY (US EPA). 2005. User's Guide for the Final NONROAD2005 Model. Technical report EPA-420-R-05-013, Assessment and Standards Division, Office of Transportation and Air Quality, United States Environmental Protection Agency, Washington D.C, U.S.

U.S. Environmental Protection Agency Clean Air Act Advisory Comittee (US EPA CAAAC). 2006. Recommendations for Reducing Emissions from the

Legacy Diesel Fleet. U.S. Environmental Protection Agency, Washington D.C, U.S.

U.S. Environmental Protection Agency (US EPA), 2009a. Potential for Reducing Greenhouse Gas Emissions in the Construction Sector. National Construction Sector, Sector Strategies Program, U. S. Environmental Protection Agency: Washington, DC, U.S.

U.S. Environmental Protection Agency (US EPA), 2009b. NONROAD Model (Nonroad Engines, Equipment, and Vehicles). Available from http://www.epa.gov/OMS/nonrdmdl.htm [cited 19 May 2009].

World Health Organization Europe, 2005. Particulate matter air pollution: how it harms health, Fact sheet EURO/04/05, World Health Organization Europe, Berlin, Copenhagen, and Rome.

APPENDIX: Table of K-S critical value

SAMPLE SIZE (N)	LEVEL OF SIGNIFICANCE FOR KS = MAX [TDF(x) - EDF(x)]				
	.20	.15	.10	.05	.01
1	.900	.925	.950	.975	.995
2	.684	.726	.776	.842	.929
3	.565	.597	.642	.708	.828
4	.494	.525	.564	.624	.733
5	.446	.474	.510	.565	.669
6	.410	.436	.470	.521	.618
7	.381	.405	.438	.486	.577
8	.358	.381	.411	.457	.543
9	.339	.360	.388	.432	.514
10	.322	.342	.368	.410	.490
11	.307	.326	.352	.391	.468
12	.295	.313	.338	.375	.450
13	.284	.302	.325	.361	.433
14	.274	.292	.314	.349	.418
15	.266	.283	.304	.338	.404
16	.258	.274	.295	.328	.392
17	.250	.266	.286	.318	.381
18	.244	.259	.278	.309	.371
19	.237	.252	.272	.301	.363
20	.231	.246	.264	.294	.356
25	.210	.220	.240	.270	.320
30	.190	.200	.220	.240	.290
35	.180	.190	.210	.230	.270
OVER 35: divide by sqrt(n)	1,07	1,14	1,22	1,36	1,63