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SUSTAINABILITY ANALYSIS OF EARTHMOVING OPERATIONS

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ABSTRACT

Emissions from construction equipment are the main contributor of environmental impacts from construction processes, and mitigating these impacts is an important aspect of operations design and planning. To this end, emission estimation models play an important role in environmental management of construction operations. This paper presents an emission model that integrates with discrete-event simulation (DES) for more accurate emission estimates from construction operations compared to existing models. The paper also presents a case study which analyzes sustainability of an earthmoving operation, to demonstrate the application of DES for estimating emissions.

1 INTRODUCTION

There is a growing need and interest to achieve sustainable development in the construction sector. Previous efforts to reach sustainability have primarily focused on the environmental performance of facilities in the "use" phase, and such efforts are lately being expanded to mitigate environmental impacts from the "construction" phase (Pena-Mora et al. 2009). Among the environmental impacts from construction processes (e.g., waste generation, energy consumption, resource depletion, etc.), emissions from construction equipment account for the largest share (more than 50%) of the total impacts (Guggemos and Horvath 2006). Controlling these emissions is therefore a critical step in the environmental management of construction processes.

To address this issue, Pena-Mora et al. (2009) proposed a framework that consists of three modules: (a) planning, (b) monitoring, and (c) controlling the emissions produced during the construction phase. Throughout the framework, the *emission estimation model* plays a vital role in supporting the selection of construction methods in the planning phase, and in providing a baseline to determine the success of "managing actions" in the execution phase. The reliability of estimates from an emission model depends largely on the accuracy of predicted productivity and utilization rates of equipment in the operation. Using discrete-event simulation (DES), a powerful tool to model complex construction operations (Martinez and Ioannou 1999), more reliable data on equipment operations can be obtained compared to current efforts for emission estimation which include using average production rates of equipment and other heuristic methods. This paper examines the limitations of current emission models and presents the methodology for applying DES to overcome these limitations. In addition, this paper describes the result of a case study on emissions generated from an earthmoving operation modeled using the STROBOSCOPE (Martinez 1996) simulation system.

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2 EMISSION ESTIMATION OF CONSTRUCTION OPERATIONS

Various efforts to estimate emissions from construction operations can be found in the literature on life-cycle analysis assessment (LCA) of construction processes (Park et al. 2003; Koo and Ariaratnam 2008; Guggemos and Horvarth 2006). These models estimate the emission of air pollutants by multiplying the amount of fuel (i.e., diesel) consumed by equipment with *fuel-to-emission conversion coefficients*. These conversion coefficients are, however, not equipment specific. The amount of fuel consumed by a piece of equipment is calculated based on its estimated total hours of operation and its energy consumption rate. Park et al. (2003), and Koo and Ariaratnam (2008) estimate operating hours using the standard bill of quantity, while Guggemos and Horvarth (2006) rely on user-estimated operating hours.

Emission inventory models for off-road diesel equipment such as NONROAD (EPA 2008a) and OFFROAD (CARB 2008) allow for more reliable estimates by distinguishing emission rates of each type of equipment. Categorized by type, model year, and horsepower group, the inventory models provide two parameters to estimate the production of various pollutants (EPA 2004): (a) *emission factor*, which is the average emission rate of a given pollutant; and (b) *load factor*, which is the average rate of maximum engine power to account for idle, partial load, and transient operating conditions. The inventory models provide *emission factors* for the pollutants CO_2, CO, NO_x, HC, SO_x and Particulate Matter (PM). Using these two parameters, the emissions from a piece of equipment for each pollutant can be calculated using the following equation (EPA 2004).

*Emissions = Engine Power(hp) * Operating hours(hrs) * Emission Factor (g/hp-hr) * Load Factor*

Using these inventory models, the road construction emission model developed by the Sacramento Metropolitan Air Quality Management District (South Coast AQMD 2008) calculates emissions per day of each air pollutants for four phases of road construction: (a) grubbing/land clearing, (b) grading/excavation, (c) drainage/utilities/sub-grade, and (d) paving. The URBEMIS (Rimpo and Associates Inc. 2007) emission model, developed to comply with the California Environmental Quality Act, uses these inventory models to estimate air pollution emissions from land development projects such as building construction. In both emission estimation models, equipment fleet size and operating hours of each equipment piece are determined using a heuristic algorithm developed from historical project data and the average production rate of various types of equipment. These models, however, have a limited utility as planning tools for environmental management of a construction project. This is mainly because they have been developed to update regional emission inventories for organizing environmental policy of local governments rather than to support the environmental management of a single construction project. The input variables of these models are, therefore, limited to several basic project characteristics, such as project area and project duration. They assume that every piece of a given equipment type has the same operation cycle for any project, (e.g., excavators have the same ratio of working and idling time across all projects). Hence, they cannot account for any variations of construction operations across projects. In other words, for projects with similar characteristics, the models will provide similar emission estimates, regardless of the differences in their operation plans.

3 APPLICATION OF SIMULATION FOR EMISSION ESTIMATION

As addressed in the previous section, current approaches cannot provide reliable results due to (1) rough estimations of operating hours of equipment, and (2) the unrealistic assumptions about equipment *duty cycles*. The application of DES to estimate emissions from construction operations could help address these limitations. Using DES to plan and design construction operations entails the creation of computer models that capture how these operations will be executed. A developed model incorporates the different resources required to execute the operation under study, the rules under which the different tasks that compose the operation are performed, the managerial decisions that must be made during the operation's execution, and the stochastic nature of events and task durations. The modeled operation can then be simulated in the computer to obtain statistical measures of performance, which typically include the cost and time of construction, resource utilization rates, waiting time and length at queues. The statistical results obtained from the simulation can help identify parts of the operation that can potentially be improved to result in time and cost savings. For the purposes of estimating emissions, a DES model can provide statistical results such as the time a given piece of equipment spends in each of its *duty cycles*, which allows for more accurate calculation of emissions. For example, a DES of an earthmoving operation can provide the time spent by an excavator in the *duty cycles* of dig, dump, swing empty, swing loaded, and idle state.

Using the statistical results from a DES model to estimate emissions, however, requires the quantification of *emission factors* for the various *duty cycles* of various equipment, which can be obtained from the emission model developed by Lewis (2009). Lewis' model provides "detailed" *emission factors* for the following seven types of equipment: (a) backhoes, (b) bulldozers, (c) excavators, (d) motor graders, (e) off-road trucks, (f) track loaders, and (g) wheel loaders. The model divides the range of engine load of each type of equipment into 10 *engine modes* and presents a method to calculate the fuel use rate for each *engine mode* based on engine power and engine tier (determined by engine age). The total fuel use rate for performing a *duty cycle* can be ascertained using the fraction of time spent in each engine mode for the duration of the *duty cycle*. This can be converted into an *emission factor* for that *duty cycle* by using the fuel-to-emission rates of each engine mode.

Using Lewis' model and results from a DES model, the emissions for each *duty cycle* can be calculated by multiplying the time spent performing the *duty cycle* with the corresponding *emission factor*. Combining the emissions from all the *duty cycles* of a given piece of equipment indicates the total emissions from that equipment. To summarize, the proposed method for sustainability analysis of construction operations can be condensed into the following steps:

1. Identify the equipment used in the operation in terms of equipment type, engine power, and engine tier.
2. Determine *emission factors* for each *duty cycle* for each piece of equipment used in the operation according to the model developed by Lewis (2009).
3. Determine the time spent by each piece of equipment performing each of its *duty cycles* for the length of the operation from a DES model.
4. Calculate and analyze the emissions generated from the operations.

4 SUSTAINABILITY ANALYSIS OF AN EARTHMOVING OPERATION

The goal of the case study presented in this section is to demonstrate the application of DES for emissions estimation. The chosen case study is from Rekapalli (2008), which is a revised and modified (to account for equipment breakdowns) version of the earthmoving operation presented in Martinez (1998). The schematic of the operation layout is presented in Figure 1. Two excavators, equivalent to the CAT 375 model with a maximum bucket capacity of 4.3 m^3, are located at the main loading area (MLA) and the alternate loading area (ALA). Nine off-highway trucks, equivalent to the CAT D30D model with a maximum capacity of 16.5 m^3, transport excavated soil from the MLA and ALA to the Dump Area along the predetermined path(s), which includes a one-way section (OWS). Trucks returning from the dump area are routed to the MLA and ALA using a "predetermined" strategy where six of the nine trucks always go to the MLA, and the rest of the trucks always go to the ALA. The strategy employed to control the flow of traffic over the OWS is "first-come-first-serve": a truck traveling in one direction can enter the OWS (thereby, establishing/maintaining a direction of traffic flow) as long as there is no truck moving in the opposite direction on the OWS.

From 250 simulation runs, with each run simulating an eight hour day of work, the operating hours of various pieces of equipment and the amount of work done (i.e., excavated soil moved) were obtained. The sustainability analysis focused on the emission of CO_2, CO, NO_x, HC and PM, all of which are produced by diesel construction equipment. CO_2 is a major greenhouse gas that causes global warming, while the other pollutants cause immediate damage to human health and the ecosystem thereby regulated by governmental standards. The following sub-sections detail the emission estimation results and analysis.

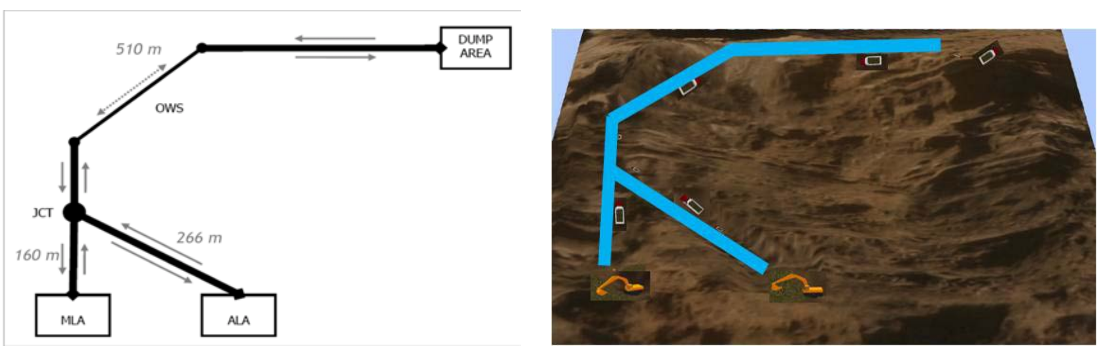

Figure 1: (a) Schematic and (b) 3D Animation of the Earthmoving Operation (Rekapalli 2008)

4.1 Emission rates of equipment

Based on the model presented in Lewis (2009), the *emission factors* of each *duty cycle* for the excavator and truck models in this case study were calculated, and are shown in Table 1. It was assumed that all pieces of equipment were of the 2005 model year, which is classified as Tier 2 in EPA's engine tier regulation (EPA 2008b). The horsepower of equipment engines were obtained from the Caterpillar Performance Handbook (ed. 28). Based on the classification in Lewis (2009), the *duty cycles* of off-highway trucks include: (a) moving, and (b) idling, while the *duty cycles* of excavators include: (a) digging, (b) hauling, (c) dumping, and (d) idling. The load difference between hauling and returning trucks is not considered. In case of equipment breakdown, it is assumed that no emissions are generated during the repair period.

Table 1: Emission rates of various duty cycles

Construction equipment	Horsepower (hp)	Duty Cycle	NO_x (g/hr)	HC (g/hr)	CO (g/hr)	PM (g/hr)	CO_2 (kg/hr)
Off-Highway Truck	285	Moving	250.9	36.95	83.45	1.915	18.77
		Idling	106.0	18.34	36.00	0.670	6.720
Excavator	428	Digging	1,056	119.4	321.4	9.621	92.26
		Hauling	1,324	152.9	413.0	11.90	115.2
		Dumping	610.5	76.71	192.0	5.231	50.51
		Idling	106.0	18.34	36.00	0.670	6.720

4.2 Operating hours of equipment

Table 2 presents the 95% confidence intervals for operation time of each *duty cycle* of various pieces of equipment, obtained from the 250 runs of the simulation model. The servicing time of the MLA Excavator is longer than that of the ALA Excavator because there are more trucks assigned to the MLA excavator. For off-highway trucks, the average behavior of all trucks is presented. Also presented in Table 2 is the amount of excavated soil from the 250 simulation runs.

Table 2: Operation time of various duty cycles (LCL: lower confidence limit, UCL: upper confidence limit)

	Excavated Soil (m^3)	Duty Cycle hours of MLA Excavator (hrs)				Duty Cycle hours of ALA Excavator (hrs)				Ave. Duty Cycle hours of Trucks (hrs)	
		Digging	Hauling	Dumping	Idling	Digging	Hauling	Dumping	Idling	Moving	Idling
95% LCL	4,731	1.430	2.502	0.536	3.193	0.740	1.296	0.278	5.336	4.769	2.796
95% UCL	4,763	1.454	2.545	0.545	3.237	0.760	1.331	0.285	5.420	4.799	2.843

4.3 Sustainability Analysis

The 95% confidence intervals of emission estimates for the case study operation are summarized in Table 3. The excavation of 4747 m^3 of soil with two excavators and nine off-highway trucks produces approximately 22 kg of NO_x, 3 kg of HC, 7 kg of CO, 0.18 kg of PM, and 1.7 tons of CO_2. These values are believed to be significant considering that the equipment fleet size is limited and the traveling distance of off-highway trucks is quite short (the dump area is located within 1 km of load areas).

Table 3: Emissions from various construction equipment

Construction equipment	NO_x (g)	HC (g)	CO (g)	PM (g)	CO_2 (kg)
Excavator 1	[5,489 - 5,582]	[653.3 - 664.3]	[1,711 - 1,740]	[48.50 - 49.32]	[468.9 - 476.8]
Excavator 2	[3,236 - 3,305]	[406.1 - 414.6]	[1,020 - 1,041]	[27.62 - 28.21]	[267.9 - 273.6]
Individual Truck	[1,494 - 1,507]	[227.7 - 229.6]	[499.1 - 503.3]	[11.01 - 11.10]	[108.4 - 109.3]
Total : Exc. 1, 2 & 9 Trucks	[22,170 - 22,450]	[3,108 - 3,145]	[7,223 - 7,311]	[175.2 - 177.5]	[1,712 - 1,733]

With the application of DES for sustainability analysis, it is also possible to compare the environmental impacts of different operation designs/strategies. Specifically, the impact of different truck fleet sizes with different "load-area routing" strategies for each fleet size were compared. For this case study, the emission cost (i.e., emission of various pollutants per cubic meter of soil moved measured as g/m^3) was used as the performance measure to compare various operation scenarios. The scenario with higher emission cost will generate more emissions for completing the same amount of work than the scenario with lower emission cost.

Table 4 presents the results of the sustainability analysis for three different routing strategies with nine trucks in the operation. In terms of the emission costs, the strategy to route six trucks to MLA and three trucks to ALA is a slightly better option than other strategies, while the strategy to route five trucks to MLA and four trucks to ALA is the best option in terms of the production rate. The results are counterintuitive, because with alternatives, in which equipment fleets are the same size, higher production does not necessarily result in lower emission costs. This might be because in this operation, production is primarily determined by the utilization rate of the excavators, while emission costs depend on the utilization rate of all equipment.

Table 4: Emission comparison between different routing strategies with 9 trucks in the operation

	5 to MLA & 4 to ALA	6 to MLA & 3 to ALA	7 to MLA & 2 to ALA
Production rate (m^3/hr)	[597.8 - 601.4]	[591.3 - 595.3]	[562.5 - 566.2]
NO_x (g/ m^3)	[4.705 - 4.716]	[4.695 - 4.707]	[4.757 - 4.770]
HC (g/ m^3)	[0.659 - 0.660]	[0.658 - 0.660]	[0.670 - 0.672]
CO (g/ m^3)	[1.532 - 1.536]	[1.529 - 1.533]	[1.551 - 1.555]
PM (g/ m^3)	[0.037 - 0.037]	[0.037 - 0.037]	[0.037 - 0.038]
CO_2 (g/ m^3)	[363.9 - 364.6]	[362.7 - 363.5]	[366.0 - 366.9]

Table 5 presents the production rate and emission costs for different truck fleet sizes (with the best routing strategy for each fleet size being compared). The production rate consistently increases as the fleet size increases. The emission cost, however, is the lowest when choosing the option of seven trucks, five assigned to the MLA and two to the ALA. Similar analysis can be performed to compare other operation designs/strategies such as using newer or different equipment, using different strategies to route trucks to the loading areas or to route the flow of traffic on the OWS.

Table 5: Emission comparison between scenarios with different number of trucks

	5 Trucks *3 to MLA & 2 to ALA*	7 Trucks *5 to MLA & 2 to ALA*	9 Trucks *5 to MLA & 4 to ALA*	11 Trucks *6 to MLA & 5 to ALA*
Production rate (m^3/hr)	[402.6 - 405.8]	[520.4 - 524.8]	[597.8 - 601.4]	[657.6 - 662.2]
NO_x (g/ m^3)	[4.580 - 4.591]	[4.550 - 4.561]	[4.705 - 4.716]	[4.832 - 4.845]
HC (g/ m^3)	[0.638 - 0.640]	[0.634 - 0.635]	[0.659 - 0.660]	[0.680 - 0.682]
CO (g/ m^3)	[1.490 - 1.494]	[1.480 - 1.484]	[1.532 - 1.536]	[1.575 - 1.580]
PM (g/ m^3)	[0.036 - 0.036]	[0.036 - 0.036]	[0.037 - 0.037]	[0.038 - 0.038]
CO_2 (g/ m^3)	[355.5 - 356.3]	[353.1 – 354.0]	[363.9 - 364.6]	[371.9 - 372.8]

In addition to emission costs, the unit cost (measured as $/$m^3$) for all fleet size options were calculated. The CO_2 emission cost and the unit cost for all the options considered are plotted in Figure 2. The unit costs were calculated combining the owning and operating cost of each equipment from the *2005 US Army Corps of Engineers Construction Equipment Ownership and Operating: Region 2,* with labor cost from the *2005 RS Means Heavy Equipment Cost Data*. Overhead and profit are not included in the unit cost calculations. The optimal fleet size in terms of unit cost coincides with that for emission cost, which is purely coincidental and will not necessarily occur in other cases. This finding, however, highlights the possibility that designing a carbon-effective operation can be cost-effective also, which contradicts a common belief that pursuing sustainability requires additional resources and/or higher operating costs.

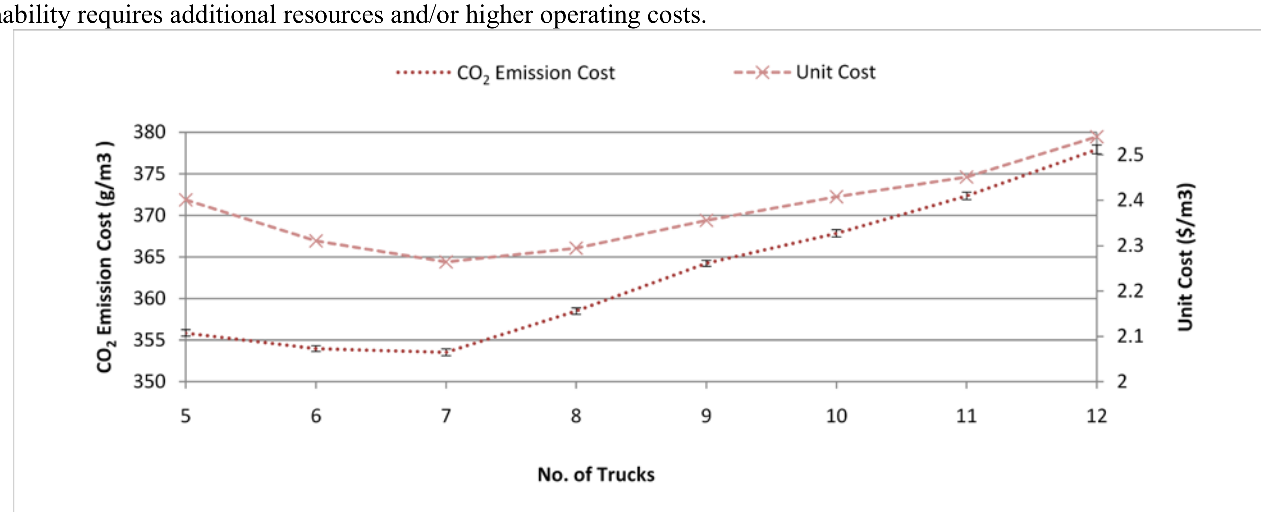

Figure 2: The optimum number of trucks for minimizing the emissions

5 CONCLUSION AND FUTURE RESEARCH

The methodology presented in this paper endeavors to integrate the emission model of construction vehicles with the simulation model of construction operations. As a result, the stochastic nature of construction operations is taken into consideration for the estimation of emissions. The preliminary case study using this methodology shows that the application of a DES model could enhance the reliability of emission estimation for construction operations and greatly help in operations-level planning in terms of minimizing the environmental impacts. As all stakeholders in construction projects become more concerned with pursuing sustainability, there are but a few methods which enable us to adequately judge the environmental impact of construction operations in the preconstruction phase. In this context, the presented methodology can serve as an effective environmental planning tool. The added value of DES provided for sustainability analysis can expand the use of the technology for operations-level planning and design by the construction industry.

This research is in its preliminary stages and there are many future directions that it can take. For starters, it is important to explore the trade-offs between time/cost considerations and emission costs when planning construction operations. This, however, also requires further investigation into developing more robust estimation models that take into account the physical properties of a construction site along with equipment performance data. For example, estimating emissions from a dump truck as it travels over a given road by taking into account various factors such as each segment's grade, rolling resistance etc., and the dump truck's engine power, torque, RPM, etc. This could take the form of a machine simulation model that integrates with a 3D animation of a DES model. In addition, by comparing with measurements from real-life operations, the validity of the developed model/methodology must be ascertained.

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