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AN INTEGRATED FRAMEWORK FOR SUSTAINABLE CONSTRUCTION
PROCESSES: UNDERSTANDING AND MANAGING THE ENVIRONMENTAL
PERFORMANCE OF CONSTRUCTION OPERATIONS

BY

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DISSERTATION

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ABSTRACT

The environmental impact from construction activities has largely been underestimated, even though these processes constitute significant economic activity. They account for a substantial amount of Greenhouse Gases (GHGs) and other diesel emissions, such as nitrogen oxide (NO_x) and particulate matter (PM). However, the efforts of contractors to reduce their construction-related air pollutant emissions remain minimal, due to (1) a lack of mechanisms to promote their voluntary efforts to mitigate such emissions, and (2) a lack of planning techniques and monitoring technologies that enable contractors to consider the environmental aspects of their day-to-day operations. Therefore, this study aims to establish an integrated management framework that encompasses the selection of green contractors, environmentally conscious planning, and environmental performance monitoring in order to facilitate environmentally sustainable construction practices.

The environmental performance of construction operations can be formulated as a function of the operational efficiency of a process, which indicates the efficient use of resources, along with the environmental properties of resources used and fuel consumed. Among the determinant factors of environmental performance, the environmental properties of resources and fuel to be used in construction operations are key parameters in determining the green capabilities of contractors in contracting. The evaluation method of the green capabilities of contractors is developed to assess the environmental properties of contractors' legacy equipment fleets. The feasibility of a multi-criteria bidding system that includes the evaluation of contractors' green capabilities is tested.

The operational efficiency is the most important and controllable factor during construction, and it is greatly affected by planning and control decisions. However, current environmental impact assessment schemes lack the capability to evaluate the impact of improving operational efficiency on environmental performance. The predictive assessment model of the environmental performance is developed to enhance current assessment schemes' capability to incorporate the operational efficiency of emission/energy resources in construction. In addition, the outcome assessment system of the environmental performance is developed to monitor the operational efficiency of emission/energy resources, based on signals captured from low-cost accelerometers. The development of such enabling tools and framework will allow construction managers to identify and capture opportunities to mitigate the environmental impact of construction operations, and to improve the operations' overall productivity.

A set of methods and tools (forming a framework) developed by this study will support the incorporation of environmental assessments into current contracting, planning, and controlling practices for construction operations. This will result in a substantial reduction of both energy use and the generation of emissions in the construction industry, by improving the operational efficiency of construction operations and by accelerating contractors' use of greener equipment and fuel.

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CHAPTER 1

INTRODUCTION

1. OVERVIEW

For over a decade, there has been a growing interest in the impact of organizations on the natural environment, particularly with regard to global warming. Environmentally conscious stakeholders, such as the government and members of society, have increasingly placed pressure on organizations to require the mitigation of the ecological footprint from their products and processes (Porter and Linde 1995). Building and construction sectors are at the forefront of confronting such environmental pressure, because their products—buildings and civil infrastructure—have long lifetimes and require significant energy to operate. Much effort, therefore, has been made in the building and construction sectors to develop energy-efficient products.

Meanwhile, the process of constructing buildings and infrastructure has not been paid much attention with regard to the sustainability efforts made by the construction and building sectors, even though construction activities as a whole consume significant amounts of energy and generate considerable levels of carbon and other diesel exhaust emissions. For example, construction is the third highest contributing industrial sector for GHG emissions, ranking just behind the oil and gas sector and the chemical manufacturing sector (EPA 2008a). In particular, the construction process of civil infrastructure produces a relatively high level of air pollutant emissions from its extensive use of energy-intensive equipment, as compared to the construction process of buildings. Public clients of civil infrastructure projects are, thereby, under increasing

pressure to mitigate air pollutant emissions from their projects.

However, the efforts made by contractors to reduce their construction-related air pollutant emissions remain minimal. This is due to (1) a lack of mechanisms to promote contractors' voluntary efforts to mitigate such emissions, and (2) a lack of planning techniques and monitoring technologies that would enable contractors to manage the environmental aspects of their day-to-day operations. Therefore, the establishment of an integrated management framework—which encompasses the selection of green contractors, environmentally conscious planning, and environmental performance monitoring—is needed for the facilitation of environmentally sustainable construction processes.

2. PROBLEM STATEMENT

There are many challenges inherent in the current practices of the environmental management of construction operations. This dissertation focuses on three specific challenges associated with mitigating energy consumption and air pollutant emissions generated from construction operations.

First, public clients require a method to evaluate the capabilities of contractors that enables the implementation of environmentally sustainable construction processes. Current efforts to control the environmental sustainability of construction operations have focused on the compliance of existing environmental regulations related to construction operations. However, existing regulatory efforts are insufficient for controlling the environmental impact of energy consumption or the air pollutant emissions from construction processes. For example, the EPA's regulations for off-road diesel engines (EPA 2004a) currently have the greatest impact on construction emissions by controlling the emission rate of newly manufactured construction

equipment. Unfortunately, the effect of these regulations is greatly offset by increases in the sheer number of engines, their operating hours, and their horsepower, as the demands of an expanding economy grow.

Construction stakeholders therefore need to mitigate the environmental effects through their own efforts to improve the environmental performance of their operation. In particular, the public clients of civil engineering projects need to lead these efforts to realize reductions in energy consumption and air pollutant emissions by contractors. A handful of public organizations have considered the mitigation of any adverse environmental impact important, and have thus provided analyses of any such impact in the planning phase. However, these analyses only compare the overall environmental impact of “No-Build” and “Build” options (ICF 2008), and do not continue after the selection between these two options. To cover this insufficiency, there exist several financial incentives that provide direct/indirect funding to contractors and equipment owners to replace old equipment with new and cleaner equipment, or to purchase emission reduction devices. Some of those incentives have reportedly resulted in effective emission reductions, but have not brought industry-wide success. Nor could they possibly bring success on such a large scale. Thus, a rigorous attempt to evaluate the green capabilities of contractors should be made in order to enable public clients to use their direct/indirect funding effectively and to involve contractors in identifying cost-effective mitigation opportunities.

The second challenge that this dissertation focuses on is that the current environmental impact assessment schemes lack the capability to appreciate the effects of planning and control decisions on environmental performance. Although current practices in construction planning are concerned only with traditional criteria—such as time, cost, and quality—the potential for

environmental impact analyses to reduce air pollutant emissions and energy consumption exists and requires the integration of these analyses into the decision-making process at the planning stage. Environmental impact assessment models for construction operations already exist, and are based on a life-cycle assessment (LCA) approach (Bilec et al. 2010; Sharrard et al. 2008; Bilec et al. 2006; Guggemos et al. 2006; Cass and Mukherjee 2010; Ries et al. 2010; Treloar et al. 2004) and nonroad equipment emission inventory models (SMAQMD 2009a; Rimpco and Associates Inc. 2007). These approaches and models provide assessments of emissions that are quite reliable, and serve effectively to develop inventories of the overall life-cycle environmental impacts of infrastructure or emission inventories at the state or local community levels. However, they have some limitations concerning operational decisions at the project level in terms of interpreting the operational efficiency from an environmental perspective. They tend to ignore a possible change in the operational efficiency caused by a different resource allocation plan and scheduling. As a result, current methods cannot provide information on the effect of planning and control decisions on the environmental performance. A method that can robustly assess the effect of operational decisions upon environmental performance thus needs to be developed and validated. A proven method would allow stakeholders to take into consideration the true environmental impact of their work in the operation design and planning stage.

The third challenge that this dissertation focuses on is the lack of a formal methodology that monitors and verifies the environmental performance of operations during/after construction. There has been extensive research on assessing the energy use and emissions from each single source utilized in construction operations (Rasdorf et al. 2010; Lewis 2007; University of California at Riverside 2007; Vojtisek-Lom 2003; Frey et al. 2002). Data on energy use and emissions at the project level is limited, however (Caltrans 1983; Stammer and Stodolsky 1995).

The assessment of energy use and emissions at the project level in the planning phase always has a great deal of uncertainty, since (1) construction projects usually involve unexpected deviations between as-planned and as-built conditions (Saidi et al. 2003; Oglesby et al. 1989), and (2) the emission factors used for estimation involve uncertainties (Frey 2007). The continuous monitoring of the environmental performance is therefore essential for taking timely corrective actions to eliminate the causes of a discrepancy between the planned and actual level of energy use and emissions.

Currently, the only available data to check the environmental performance of a construction project is the daily report on the use of equipment, which tracks how many pieces of equipment are deployed on a jobsite. This data is used to quantify the environmental impact of equipment in most LCA research on construction processes (Bilec et al. 2006; Cass and Mukherjee 2010). However, these reports contain only information on whether equipment is employed, rather than how long and how efficiently it is employed. Other information is not considered important in the current scheme of construction management. The lack of disaggregated data hinders the accurate monitoring of environmental performance. Monitoring and analyzing tools, coupled with on-site data collection methods to enable accurate measurement, are necessary for improving accounting reliability and increasing communication between participants during the construction phase of a project.

3. RESEARCH OBJECTIVES

The overall goal of this dissertation is focused on the development of an integrated framework and supporting tools that enable construction stakeholders to assess and improve the environmental performance of construction operations (in terms of energy consumption and air

pollutant generation). To accomplish this goal, the main objectives of this dissertation are as follows:

Objective 1: Develop methods that evaluate contractors' capabilities to perform environmentally sustainable construction operations.

Research Questions: What are the key parameters that determine contractors' abilities to minimize energy consumption and air pollutant generation? How can these parameters be evaluated and interpreted in a way that public clients are able to understand? How can such evaluations be integrated into contractors' selection processes in current contracting and bidding practices? To what extent can contractors' adoption of mitigation measures affect the integrated bidding process?

Hypothesis: The potential energy use and air pollutant emissions of contractors can be estimated based on key parameters that indicate contractors' green capabilities. The environmental cost caused by their estimated construction energy use and emissions can be calculated as a standardized monetary value. Contractors' adoption of mitigation measures will have a notable impact on their environmental cost, thereby affecting the integrated bidding process.

Significance: Achieving this research objective will enable public clients to have objective criteria when evaluating contractors' green capabilities. Including the environmental cost of construction emissions as a criterion in the bid evaluation process will encourage contractors' efforts to reduce the emissions that arise from their activities. Public clients can achieve greener construction practices with less additional expenditure by letting contractors compete on the cost-effectiveness of their mitigation plans. Contractors will be able to capitalize on their efforts to enhance the environmental property of their legacy equipment fleet.

Objective 2: Formulate environmental impact assessment models that robustly incorporate the effect of planning and control decisions on the environmental performance of construction operations.

Research Questions: How can the analysis of the operational efficiency of equipment be incorporated into assessing the environmental performance of operations? Which planning decisions in construction operations affect the level of the environmental performance, and to what extent? How can these decisions be represented when modeling the environmental aspects of construction operations? How can users be helped in testing the impact of their planning decisions?

Hypothesis: The operational efficiency of each piece of equipment will greatly affect the environmental performance of overall operations. Incorporating the operational efficiency of equipment into an estimation of the environmental performance greatly facilitates planning for sustainable and economical operations. Each planning decision results in different levels of environmental performance for construction projects; these levels can be evaluated with robust analysis methods.

Significance: Achieving this research objective will improve methods that integrate the environmental impact assessment with a validated approach that incorporates managerial aspects of construction operations. Construction managers would be able to evaluate the potential impact of their plans on environmental performance, and thereby make decisions that enhance the environmental performance. Decision-supporting tools will enable project managers to study and coordinate the various sustainability factors associated with their particular construction sites, and to communicate their findings with other project participants.

Objective 3: Identify monitoring methods and supporting tools to track the environmental performance of construction operations in an economically and technologically practical way.

Research Questions: Which methods and technologies can aid in the reliable monitoring of the environmental performance of construction operations in an economically feasible fashion? How can this information be organized and efficiently delivered to construction managers, permitting them to examine the environmental impact of their projects, and so make the appropriate decisions to ensure sustainable construction?

Hypothesis: A mix of data collection schemes and available sensing technologies will enable the reliable and feasible monitoring and verification of the environmental performance of construction operations.

Significance: Achieving this research objective will facilitate the establishment of a formal methodology that can monitor and verify the environmental performance of construction operations. An integrated monitoring system would also allow construction managers to track the environmental performance of their day-to-day operations and to evaluate the effectiveness of actions planned to reduce any adverse environmental impact. Data set to be provided by an integrated monitoring system would provide a basis for improving the modeling and analysis of the environmental aspects of future operations.

4. THESIS ORGANIZATION

- Chapter 2 provides the background information that supports this dissertation. It describes the following: the environmental impact caused by construction processes, previous studies to assess the environmental impact of construction processes, and the existing regulatory and voluntary efforts to control that environmental impact.
- Chapter 3 discusses key factors that determine the environmental performance of construction operations, as well as the integrated framework to manage those factors. The requirements for each component of the integrated framework are also discussed.
- Chapter 4 describes the evaluation of contractors' green capabilities. It discusses environmental consideration in construction contracting, and proposes new bidding methods that include the environmental cost of construction emissions. An illustrative example of the proposed bidding methods is described using a bid for a highway reconstruction project.
- Chapter 5 presents the predictive assessment model that incorporates the analysis of operational efficiency into quantifying the exhaust emissions from construction operations. Case studies are also presented to examine how, and to what extent, the planning decisions affect the amount of air pollutants emitted from construction operations, and to identify the impact that possible alternatives have on the schedule and cost of projects.
- Chapter 6 describes the development of the monitoring system for the operational efficiency and environmental performance of construction operations. Based on the review of existing enabling technologies, the application of smart sensors is discussed. The test results of real-world operations are also presented and discussed.

- Chapter 7 summarizes the proposed main approaches, the contribution of research, and the key conclusions. Future directions for managing and improving the environmental performance of construction operations are also discussed.

CHAPTER 2

RESEARCH BACKGROUD AND LITERATURE REVIEW

1. INTRODUCTION

Currently, the significance of environmental impacts from construction processes has not been well understood because the decentralized nature of construction processes—employing a number of subcontractors—has hindered accurate quantification of their environmental impacts. In addition, the characteristics of construction processes—the uniqueness of each project and the high degree of fragmentation—make it difficult for firms to pursue a continuous improvement of their processes, and also limit the ability of governmental agencies to develop effective environmental regulations and incentives to regulate and stimulate the creation of environmentally sustainable construction processes.

This chapter therefore investigates the energy consumption and associated air emissions of construction sectors in the United States and Canada, and reviews existing studies to quantify the environmental impact of a construction project. This chapter also examines the existing regulatory and voluntary efforts to control the environmental impacts from construction processes. The United States and Canada generate around 20% of global GHG emissions from fossil-fuel burning (CDIAC 2009). They also lead the world in environmental legislation knowledge, and their environmental legislation is highly interconnected. The investigation of construction sectors in the United States and Canada thus provides insights into the opportunities and challenges for the reduction of energy consumption and air emissions for the construction industry globally.

2. ENERGY CONSUMPTION AND AIR EMISSIONS FROM CONSTRUCTION SECTORS IN THE UNITED STATES AND CANADA

2.1. Energy consumption and GHG emissions

Table 2.1 summarizes the GDP, energy consumption, and GHG emissions from construction sectors in United States and Canada in 2006. Economic output from construction sectors accounts for 4.9% of the GDP of the United States and 6.0% of the GDP in Canada (US BEA 2009; Statistics Canada 2009); the actual impact of the construction industry on the economy is generally considered to be higher than the composition of GDP due to its effects on employment and investment. Construction's share of the GDP has steadily increased in Canada over the last decade, while it has fluctuated slightly in the United States.

Table 2.1. Energy use and GHG emissions from construction sectors in the United States and Canada in 2006 (US BEA 2009; Statistics Canada 2009; EPA. 2009a; NRCan's OEE 2009a; Fergusson 2008).

	GDP* (nominal billion US \$)	Share in national GDP	Energy Consumption (trillion Btu)	Share in national energy consumption	GHG emissions (Tg)	Share in national GHG inventories
US	649.4	4.90%	913.9	1.2%	67.2	1.2%
Canada	75.4	5.95%	57.5	0.7%	4.2	0.9%

* Adjusted based upon the nominal billion values of U.S. total GDP and Canada's total GDP in Fergusson's report (NRCan's OEE 2009a)

Aggregate data on energy consumption and GHG emissions in the U.S. construction sectors can be found in the U.S. Environmental Protection Agency (EPA)'s inventory report for greenhouse gas emissions and sinks, which was submitted to the United Nations framework convention on climate change (EPA 2009a). The report summarizes data for energy consumption and GHG emissions from the operation of off-road construction/mining equipment. It is reported that in 2006, construction equipment consumed 5,968 million gallons of diesel, equivalent to 827.8 trillion Btu at 138,700 Btu/gal, and 688 million gallons of gasoline, equivalent to 86.04

trillion Btu at 138,700 Btu/gal. As total construction industry use in 2006 was 913.85 trillion Btu, the industry represented 1.2% of total U.S. energy consumption. This level of energy consumption is higher than the combined total of all residential households in California, which is one of most populous states (EIA 2006). The GHG emissions resulted from this level of energy consumption were reported to be 67.2 Tg (Teragrams), corresponding to approximately 1.2% of total U.S. GHG emissions from fossil fuel use. Another EPA's report on key industrial sectors (EPA 2008) has estimated from energy expenditures of industrial sectors (DOC 2005) that construction produced 131 million metric tons (MMT) of CO₂e (1.7% of total U.S. GHG emissions) in 2002. This places the construction industry as the third highest contributor of GHG emissions among all U.S. industrial sectors.

However, this level of energy consumption and its associated GHG emissions did not account for on-site energy consumption from the use of electricity and natural gas. The share of electricity and natural gas in total energy consumption of the construction sector was estimated to be 10 to 25% and 13 to 15%, respectively in 2002 (Sharrard et al. 2007) . In addition, Sharrard *et al.*(2007) offer useful insights that take into consideration the energy consumption of the on-road trucks employed in the construction sectors; they contend that the construction sector share could have been 2.6 to 3% of total U.S. energy consumption in 2002, if the use of on-road trucks was included (the construction sectors accounts for 6% of light on-road truck use and 17% of medium/heavy truck use in the U.S.).

Canada's annual inventory report for greenhouse gas emissions and sinks (Environment Canada 2008a) states that construction sectors account for 0.2% of national energy consumption. This data, however, likely underestimates the actual energy consumption from construction sectors, since it has assigned the energy use of construction equipment to transportation sectors

rather than construction sectors. The data in this report for transportation sectors does not give any guidance on disaggregating the energy use of construction equipment from other transportation sources. The available source on consumption for construction equipment use is the National Energy Use Database from the Office of Energy Efficiency (NRCan's OEE 2009a). This source reports that, in 2006, the Canadian construction sector consumed 57 trillion Btu of energy, accounting for 0.8% of Canada's total energy consumption, and generated 4.2 Tg CO₂ equivalent of GHG, accounting for 0.9% of Canada's total GHG emissions. This level of energy consumption and GHG emissions roughly corresponds to the electricity consumption of all residential households in British Columbia (NRCan's OEE 2009b). Unfortunately, this source also potentially underestimates the energy consumption and GHG emissions of the construction sectors, since the figures do not include the use of on-road trucks.

Approximately 90 percent of the energy consumed in construction is produced through fossil fuel combustion, utilizing diesel, gasoline, and natural gas (EPA 2009b). The remaining 10 percent comes from purchased electricity. Diesel, gasoline, and natural gas consumption in construction in turn accounts for 64%, 20%, and 16% of total fossil fuel combustion (respectively) in the U.S. (EPA 2008). Diesel is the major energy source for construction due to the predominant use of diesel engines in construction equipment. The two biggest sources of energy consumption in construction are the on-site operation of construction equipment and the on/off-road transportation of materials, equipment, and waste (EPA 2009b; Bilec et al. 2007; Guggemos and Horvath 2006). The rest of energy is consumed by the use of on-site electricity for small equipment, temporary lighting, and trailers, as well as for employee commuting and other miscellaneous site-related activities. The major opportunities to reduce GHG emissions in construction can thus be found in the operation of on-site equipment and off-site transportation.

For example, contractors could mitigate emissions through the replacement of old equipment with pieces that are new and energy-efficient, as well as by using cleaner fuels. By reducing transportation loads, the reduction of waste and the use of locally manufactured/supplied materials could contribute further to the decrease of GHG emission levels.

Construction subsectors have quite different patterns of energy use and GHG emission generation, depending on the characteristics of their operations. According to EPA (2009b), heavy and civil engineering generates 26% of total carbon emissions, while building construction accounts for 32% and specialty trade contractors produce 42%. However, when comparing emission intensities which indicate emissions per unit of output (typically the dollar value added by the industry for industry-specific emission intensities), heavy and civil engineering ranks higher than either building construction or specialty trade contractors. In particular, highway, street, and bridge construction show the greatest emission intensity, two times higher than the average emission intensity for the construction sector as a whole. This means road, street, and bridge construction has greater opportunities for reducing GHG emissions, and thereby the role of public transportation agencies, which mostly execute road, street, and bridge construction, is important in mitigating GHG emissions from construction of transportation facilities.

2.2. Other diesel exhaust emissions

In addition to GHG, particulate matter (PM), sulphur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) are regulated by governmental standards as Criteria Air Pollutants (CAPs) in the U.S. and as Criteria Air Contaminants (CACs) in Canada (EPA 2012; Environment Canada 2009b); they are major contributors to smog, acid rain, and other health hazards. The CAP emissions from construction sectors in the United States and Canada in 2006 are summarized with their share in national CAPs inventories in Table 2.2.

The NONROAD model of the U.S. EPA (EPA. 2009c) provides data for these criteria air pollutants from construction equipment, based on an estimation of engine population and fuel consumption. Among criteria air pollutants, construction equipment causes a disproportionately high share of PM_{2.5} and NO_x in national inventories, equivalent to 2.1% and 3.9% respectively, compared to its share in national GHG inventories. PM directly contributes to health problems such as asthma, lung cancer, and heart disease, and NO_x causes ozone and climate change problems.

Table 2.2. CAP emissions in metric tonnes from construction sectors in the United States and Canada (EPA. 2009c; Environment Canada. 2008c)

		PM ₁₀	PM _{2.5}	SO _x	NO _x	VOC	CO
US	Exhaust emissions	64,530	62,489	94,200	688,862	110,329	1,094,515
	Share in national total	0.4%	2.1%	0.7%	3.9%	0.6%	1.2%
Canada	Exhaust emissions*	9,365	8,988	5,141	141,482	12,943	71,457
	Share in national total	0.2%	0.7%	0.3%	5.5%	0.04%	0.6%
	Fugitive emissions	1,100,422	218,012	661	2,080	24	342
	Share in national total	18.1%	16.3%	0.0%	0.1%	0.0%	0.0%

* The amount of exhaust CAC emissions from construction processes is available upon request; this data is not revealed in annual NPRI reports.

As with the estimation of GHG emissions, if the use of on-road trucks in construction is included, the CAP emissions from this industry would increase by 32% for PM₁₀, 96% for NO_x and 125% for VOC (Sharrard et al. 2007). In addition, besides the emissions from fuel combustion for operating construction equipment, which are called exhaust emissions, construction operations in an outdoor and open space work environment directly generate a huge amount of CAP emissions, such as dust from soil erosion, rock crushing, and building demolition; these emissions released into the air from sources other than the tailpipes of construction equipment are called fugitive emissions. Fugitive emissions are not included in this estimation, however, since the inventory of fugitive emissions from construction operations has not been

published.

In Canada, the National Pollutant Release Inventory databases (NPRI) (Environment Canada 2008c) provide data on both exhaust and fugitive CAC emissions from construction processes. Exhaust emissions from Canadian construction sectors are assessed using an approach similar to that of the NONROAD model of the U.S. EPA; they cause a high share of NO_x in Canada's national inventories, equivalent to 5.5%. The estimation does not include the use of on-road trucks in the construction sector, however. Fugitive emissions resulting from construction operations are estimated using emission rates based on the construction area; they dominate nationwide PM emissions, accounting for 18% of PM_{10} and 16% of $\text{PM}_{2.5}$ in Canada's national inventories.

This investigation illustrates that energy consumption and air emissions from the construction industry in governmental estimates are significant when looked at from various perspectives and that construction processes in particular have been a major source of CAP emissions. Furthermore, governmental estimates of energy consumption and air emissions on the construction sectors may differ widely from the actual environmental impact of construction processes because they do not include several major sources of energy consumption and emissions. Therefore, more accurate inventories for construction processes must be acquired to understand the environmental impact of the construction industry relative to that of other industrial processes. To address these concerns, it is necessary to develop the reliable methodology to quantify emissions from a construction project, which will enable a bottom-up emission inventory, starting from each single construction project, to be developed.

3. ENVIRONMENTAL IMPACT ASSESSMENT OF CONSTRUCTION PROCESSES

One approach to assess the total environmental impact of construction processes is to use life-cycle assessment (LCA). This method has been used widely for evaluating the total environmental effects over the life-cycle of commercial and residential buildings—from raw material extraction for manufacturing building components to maintenance and a building's end-of-life. Most current LCA tools for the entire life-cycle of a building overlook or improperly address the environmental impact from construction processes (NIST BFRL 2009; Athena Institute 2009; BRE 2009). Conversely, only a few LCA analyses of construction processes have been attempted (Guggemos and Horvath 2006; Bilec et al. 2010; Sharrard et al. 2008; Ochoa et al. 2005). The process-based LCA utilizes a process-flow diagram for computing known environmental inputs and outputs at each process, such as energy, emissions and wastes (Fava et al. 1991). The boundary of a process-flow diagram should include all the upstream environmental effects along the supply chain of materials and services for constructing built environment, in order to holistically assess the environmental effects of a process. However, due to data constraints, the boundary of process-based LCA is typically set at a level where some upstream effects are left out of the boundary. The I-O LCA method allows this problem to be simply addressed by using national sector-by-sector economic interaction data, which quantifies direct and supply-chain effects between sectors in an entire economy (Hendrickson et al. 1998). The I-O LCA provides average and general analysis of the environmental impacts generated by certain levels of economic demands in a sector, whereas the process-based LCA provides a process-specific analysis of environmental impacts. Therefore, a hybrid approach combining the advantages of both models is generally used in attempts to assess the environmental impact of construction processes.

Ochoa *et al.* (2005) attempted to calculate the environmental impact of construction on a typical residence in Pittsburgh, PA, which is a two-story wood-frame building with 186 m² of living space. For this case study, Ochoa *et al.* (2005) relied on the I-O LCA method using Carnegie Mellon University's Economic Life Cycle Assessment tool (EIO-LCA) (CMU GDI 2009). With the results of a construction cost estimate of a case building, Ochoa *et al.* (Athena Institute 2009) mapped the cost for various materials and works to the EIO sectors of the EIO-LCA model. Construction processes for a typical residence thus were estimated to consume 550,000 MJ of energy, producing 43 CO₂ equivalent tonnes of GHG, 200 kg of NO₂, 300 kg of CO, and 100 kg of PM₁₀. Sharrard *et al.* (2008) present the I-O-based hybrid LCA model for the construction industry; it allows users to create a modified direct supply chain for their custom products based on the current EIO-LCA matrix. Sharrard *et al.* (2008) updated and reformulated the construction sector data in the current EIO-LCA model to account for 2002 benchmark of national-level environmental data; instead, the current EIO-LCA model employs 1997 data. Using this reformulated I-O-based hybrid model, Sharrard *et al.* (2008) re-analyze Ochoa's case study, and estimate that it generated 95 CO₂ equivalent tonnes of GHG, 320 kg of NO₂, and 290 kg of PM₁₀—approximately 120%, 60%, and 190% larger than Ochoa's estimate, respectively.

Guggemos and Horvath (2006) present an augmented process-based hybrid model for construction processes, which employs a process-based LCA with process description of a case project and uses EIO-LCA for estimating energy use and emissions from the production of the temporary materials for construction processes. Using this model, Guggemos and Horvath (2006) estimate the environmental impact of the construction of the structural frame of a set of four-story office buildings in California with an area of 8,760 m². The project was estimated to consume approximately 4,180 GJ of energy and generate 291 tonnes of CO₂, 2,466 kg of NO₂,

1,997 kg of CO and 321 kg of PM₁₀. With a similar process-based hybrid model, Bilec *et al.* (2010) analyze the environmental impact from the construction of a five-story precast concrete parking structure with 377 parking spaces in Pittsburgh. Unlike Guggemos and Horvath (2006), Bilec *et al.* (2010) include construction service sectors and the upstream production/maintenance effects of construction equipment in the boundary of the analysis; EIO-LCA is used for assessing their environmental impact. Bilec *et al.* (2010) use as-built data for determining the input of analysis, whereas previous efforts mostly relied on as-planned data. This project is calculated as generating 682 tonnes of CO₂, 6,705 kg of NO₂, 3,540 kg of CO and 420 kg of PM₁₀. Bilec's hybrid model shows estimates of CO₂ emissions two times larger than Guggemos and Horvath's model for a case study on the construction of a steel frame; Bilec's estimate, however, is only about 17% of the estimates based on the EIO-LCA method (Bilec 2007).

Another approach focuses on estimating the emissions from operating construction equipment, whereas the LCA-based approach includes other environmental aspects of construction processes in its scope. These efforts are mostly based on off-road equipment emission inventory models such as NONROAD (EPA. 2009c) and OFFROAD (CARB 2009a), and provide more reliable estimation on the emissions from operating construction equipment than the LCA-based approach by employing emission rates for each type of equipment. The road construction emission model developed by the Sacramento Metropolitan Air Quality Management District (SMAQMD 2009) calculates the amount of air pollutant emissions for four phases of road construction: (a) grubbing/land clearing, (b) grading/excavation, (c) drainage/utilities/sub-grade, and (d) paving. The URBEMIS emission model (Rimpo and Associates Inc. 2007) estimates air pollution emissions from land development projects such as building construction. In these emission estimation models, equipment fleet size and the

operating hours of each equipment piece are estimated using a heuristic algorithm developed from historical project data.

All these efforts have contributed to a better understanding of the environmental impact of construction processes, which previously had been underestimated, and have provided a decision-support tool for stakeholders to create an environmentally sustainable construction process. However, these efforts are still in development and need to improve the reliability of their results. Comparing the results of these efforts is difficult due to the unique qualities of each case study and the differences between each analysis boundary. In addition, even when a comparison is possible, there is little data on actual energy use and emissions in real-world scenarios to validate those comparisons. The use of rapidly advancing technologies for sensing the exhaust emissions from vehicles and monitoring on-site air quality could provide the necessary real-world data to enhance the development and validation of a robust emission simulation model.

4. EXISTING REGULATORY AND VOLUNTARY EFFORTS TO CONTROL EXHAUST EMISSIONS FROM CONSTRUCTION OPERATIONS

Many efforts have been implemented to enhance the environmental sustainability of the construction process at four management levels: environmental cooperation routines, environmental technology policies, environmental regulations, and environmental incentives. Table 2.3 summarizes the existing efforts to control the energy consumption and GHG/CAP emissions from construction processes in the United States and Canada. Thus far, governmental regulatory efforts rather than voluntary private sector efforts have led the way toward environmentally sustainable construction processes. Most of these regulatory efforts have

focused on reducing CAPs from construction processes, since the environmental impact of CAP emissions from construction diesel equipment has been relatively well-recognized. In comparison, the efforts associated with reducing GHG emissions from construction processes are nascent, but have been increasing in demand recently. This is due to the recent definition of GHGs as air pollutants under Clean Air Act legislation in the United States and Canada (EPA 2009d; Hierlmeier 2006).

Table 2.3. Current efforts on reducing energy consumption and air emissions from construction processes in United States and Canada.

Management Levels	Current Efforts in North America
Environmental Cooperation Routines	Green Building Certification—Leadership in Energy and Environmental Design (LEED) Environmental Management System—ISO 14001 certification
Environmental Technology Policies	Environmental Technology Verification program U.S. EPA’s SmartWay Transport Partnership
Environmental Regulations	Nonroad rules : “Tier 1”, “Tier 2”, “Tier 3”, “Tier 4 transitional”, and “Tier 4 Final”
Environmental Incentives	U.S. EPA’s National Clean Diesel Campaign California Carl Moyer Program, Texas Emissions Reduction Plan

4.1. Environmental Cooperation Routines

The U.S. Green Building Council (USGBC)’s Leadership in Energy and Environmental Design (LEED) green building rating system (USGBC 2009) is a certification program that has been widely accepted as a benchmark for the design, construction, and operation of green and sustainable built environments in the United States. Canada also has its own LEED rating system, which has been tailored specifically for Canadian climates, construction practices, and regulations (Canada GBC 2009). The LEED green building rating system is concerned mostly with the design of green buildings which require less energy for operation, and with the processes to implement the design properly. This rating system provides a list of credits measuring the environmental performance of construction processes in terms of sustainable site

development, energy efficiency, and selection of materials (USGBC 2009). However, with regards to energy consumption and the associated emissions from construction processes, this system is concerned only with fugitive dust emission prevention and the reduction of material transportation, which can be achieved from the use of regional materials, and the reuse of existing building components. It does not provide any credit to address directly exhaust emissions from operating construction equipment, which is the highest contributor of emissions from construction processes.

The adoption of Environmental Management Systems (EMS) allows an organization to identify opportunities for reducing the environmental footprint of its day-to-day operations. Many construction companies already have components of an EMS in place that they can develop further, such as written and unwritten procedures, best management practices, and regulatory compliance programs (ICF 2005); however, few construction companies in North America have a full EMS system (Christini et al. 2004). The International Organization for Standardization (ISO) 14001 serves as the standard for developing and implementing an effective EMS. The ISO 14001 approach facilitates an organization-wide investigation of all the environmental aspects of its activities and builds the framework for continual improvement of environmental performance. This can lead to the reduction of environmental impact including waste generation, energy consumption, air emissions and material use. Also, by achieving ISO 14001 certification, an organization can enhance its reputation as an environmental leader and gain a competitive advantage in some markets. However, this standard has not been accepted widely by construction companies in the United States and Canada (ICF 2005); in contrast, many companies in the manufacturing sectors have achieved certification. The biggest challenge for implementing EMS to comply with the ISO 14001 standard is that the unique qualities of each

construction project makes it difficult to pursue the continuous improvement of processes by monitoring environmental performance over time, that is suggested by the ISO 14001 standard (Krizan 1999). Since none of construction processes are repeated under the same conditions, comparing the environmental performance of a construction process on one project with that of previous projects cannot provide a concrete basis to judge the improvement of its environmental management. Another challenge is that most construction firms are small, making it difficult to establish and maintain a company-wide ISO 14001 EMS (ICF 2005).

4.2. Environmental Technology Policies

The U.S. EPA's Environmental Technology Verification (ETV) program provides the verification process for the performance of innovative environmental technologies in a particular application (EPA 2009f). The ETV program ensures that state governments can be confident that the proposed emission reduction effect of new technologies is achieved when a state takes credit in a State Implementation Plan, which is imposed by the EPA for regulating emissions at the state level. In the construction sector, the ETV program has largely been concerned with the technologies for CAPs emission reductions, such as after-treatment technologies, use of cleaner fuel, and emission-reducing fuel additives. The amount of emission reduction achieved by these technologies in the real world is verified by the rigorous testing procedures of the ETV program. New technology that passes the EPA verification process is added to EPA's Verified Technology List.

This ETV process is essentially voluntary, and it can be initiated and paid for by manufacturers of environmental technologies. Manufacturers are motivated by purchase and lease agreements with contractors who are seeking environmental incentives at the national and state levels, as will be discussed below. Those incentives require contractors to verify the amount

of emission reduction with EPA's Verified Technologies process. Canada's Environmental Technology Verification program offers a similar verification process under a license agreement with Environment Canada (2009d). California, which is traditionally proactive in pioneering environmental initiatives, has its own verification process for diesel emission reduction technologies, called the Diesel Emissions Control Strategy Verification program (Cal EPA 2009). It has some differences in comparison with the EPA program, such as with emission reduction classification and the test methods for measuring emission reduction. Only a few products have been verified by these programs for off-road use, however, even though there exist many verified products for on-road use.

The SmartWay Transport Partnership is a voluntary collaboration between the U.S EPA and various freight industry stakeholders (US EPA 2009f). SmartWay partners are committed to improving energy efficiency and reducing GHG and air pollutants emissions from their freight delivery operations; they benefit from the SmartWay brand to project the image of an environmental protector. To become a partner, owners must measure the current environmental performance of their vehicle fleets and improve their transportation emissions within three years. EPA has provided the Freight Logistics Environmental and Energy Tracking (FLEET) Performance model to assist stakeholders in measuring their current fuel use and emissions, as well as in evaluating the costs and effectiveness of emission reduction strategies that they might adopt in the future. One distinctive aspect of the strategies suggested by this partnership is that, besides technological strategies, operational strategies, such as idling reduction and productivity improvement, are considered significant. This program also provides financial support for the implementation of diesel emissions reduction technologies in transportation. Further, it can be applied to the vehicle fleets for transporting materials, waste, and equipment for construction

processes; this is important since transportation incurs a large share of the environmental impact of construction processes, especially in cases where the job site is located in an isolated area. Under current circumstances, however, there is little motivation for contractors to employ a SmartWay partner for their transportation needs.

4.3. Environmental Regulations

The U.S. EPA's rules for off-road diesel engines are the regulations with the biggest impact on emissions from construction equipment. These rules classify off-road diesel engines by the year of manufacture and horsepower of engines, and they specify the allowable emission rates of combined NMHC + NO_x, PM, CO and HC for each group, named successively "Tier 1", "Tier 2", "Tier 3", "Tier 4 transitional", and "Tier 4 Final" (EPA 2004a). The higher tiers address more recently manufactured engines with more stringent regulations. Equipment manufacturers are required to ensure their products comply with these regulations with a standardized certification test for their products. Canada also applies these rules to its off-road equipment, since all off-road diesel engines in Canada are imported, and about two-thirds of those are manufactured in the United States (Environment Canada 2009e). These rules have resulted and will continue to result in reductions of regulated air pollutants emissions. For example, under Tier 3 rates, which are effective from 2006 to 2010 for engines with horsepower range $175 \leq \text{HP} < 300$, typical of engines used in excavators and graders, engines are expected to reduce their emission rates by 63, 69 and 62 percent of PM, CO, and combined NMHC+NO_x, respectively, relative to engines designed to comply with Tier 1 rates (EPA 2004a).

However, these rules have several definite limitations in regard to the control of GHG/CAP emission from construction processes. First, these regulations do not have a rule for

GHG emissions, since GHG, as mentioned, was not previously considered as an air pollutant under the Clean Air Acts. Although the EPA now is seeking a way to develop regulations for GHG emissions from off-road vehicles, even the rules that will be newly developed would not regulate all the construction equipment for a reason that will be described later. Another issue is that engines manufactured before 1996 were not affected by these regulations and many pieces of construction equipment manufactured before 1996 are still in use as the average lifetime of construction equipment is relatively long—15 to 20 years and sometimes even longer. Consequently, a large share of in-use construction equipment is not affected by these regulations. Thus, even after issuing regulations on GHG emissions, only newly manufactured equipment would be affected. Finally, these rules are concerned only with the emissions rate of engines, rather than the actual amount of emissions produced by construction processes. Even if the emission rate of construction equipment is reduced, the emissions from construction processes may be still considerable due to the increase of both engine populations and operating hours for construction equipment, which continue to grow as the economy expands.

4.4. Environmental Incentives

As addressed in the previous section, a large share of construction equipment is not affected by the governmental regulations. Voluntary innovation by the stakeholders in the construction sector on this issue, however, is rare since the cost for improving the environmental performance of equipment outweighs the short-term benefits. In this context, environmental incentives are required to spur the efforts of stakeholders. There are two types of environmental incentives for reducing emissions from construction processes: grant programs, which provide direct funding to equipment owners to replace old equipment with new and cleaner equipment, and tax incentives,

which offer tax exemptions, tax deduction, or tax credits to spur the use of technologies for reducing emissions.

The U.S. EPA's National Clean Diesel Campaign (NCDC) is a nationwide grant program that provided \$5 million in 2006 for supporting the adoption of cleaner diesel technologies and strategies, such as cleaner fuels and diesel retrofit devices (diesel oxidation catalysts, diesel particulate filters, engine replacement, *etc.*) (US EPA 2009g). Along with West Coast Collaborative (WCC 2009), which provides additional funding resources, this grant program has reportedly resulted in effective emissions reductions in many case projects, such as the Central Artery/Tunnel Project (the Big Dig), the I-95 New Haven Harbor Crossing Improvement Program, and the South Ferry subway project. At the state level, California's Carl Moyer Program is the first successful statewide grant program, which has provided over \$154 million of incentive grant funding—5 percent to construction equipment and 45 percent to on-roads (trucks)—since it began in 1998 (CARB 2009b). This program has selected projects based primarily on the cost-effectiveness of emissions reduction. The Moyer program has focused on NO_x reductions; as a result, the projects funded by the Moyer Program are estimated to have reduced NO_x emissions by 5,100 tons per year in its first four years at an average cost-effectiveness of approximately \$3,000 per ton (ICF 2005). The Texas Emissions Reduction Plan (TERP), modeled after the Moyer program, is also a state-level grant program focused on diesel emission reductions (TCEQ 2010). TERP provides a surcharge on the incremental costs associated with activities to reduce NO_x emissions for a project, which is selected in competition based on its cost-effectiveness. In its first three years, TERP has awarded more than \$120 million in grants to approximately 280 projects—around one-third of the projects have involved construction equipment (TCEQ 2010). The cost-effectiveness of these projects averages about

\$5,700 per ton of NO_x emission reduced (ICF 2005).

Regarding tax incentives, there have been some tax incentives at the state level for spurring the retrofit or repowering of diesel engines or promoting the use of alternative fuels. Oregon offers an income tax credit of up to 35 percent of the cost for purchasing and installing emissions reduction equipment (Oregon DEQ 2009); Georgia offers an income tax credit of 10 percent of the cost (up to \$2,500) of diesel particulate emission reduction equipment (ICF 2005). Tax incentives have explicit advantages over grants. They can be utilized at any time and are not subject to the exhaustion of funds; in contrast, grant programs require a company's business cycle to be synchronized with the granting schedule and can only be awarded to a limited number of projects due to funding constraints. However, tax incentives have not been used effectively, mainly because they are not large enough to cover the additional costs of adopting emissions reduction technologies (ICF 2005). Another issue regarding tax incentives is that small companies, which occupy a large share of the construction industry, do not make large profits and do not bear a large tax liability. Tax incentives for GHG emissions from construction processes have not yet been developed. However, support for a carbon tax (a tax on carbon dioxide emissions from the use of fossil fuels during the manufacturing process of a product) in the United States is increasing steadily among public officers and economists. If such a tax is introduced, there would be a high possibility of developing tax incentives that would be very effective for construction industry stakeholders, for example, by providing an exemption from the carbon tax for energy-efficient construction projects.

5. SUMMARY

Energy consumption and air pollutant emissions from construction processes have reached significant levels. Energy consumption in the U.S from the use of off-road construction equipment is equal to that of all residential households in California combined, while energy consumption in Canada is equal to the total electricity usage of all residential households in British Columbia. Criteria Air Pollutants (CAPs; Criteria Air Contaminants in Canada) from the use of construction off-road equipment, which have immediate and adverse effects on both the environment and human health, have an even higher share at the national level, compared to the share that construction processes hold national GHG inventories. Further, it should be noted that these amounts could be highly underestimated, since on-road vehicle use and on-site electricity/natural gas use are not included in estimation metrics. If all these sources in construction processes are considered, the national share for construction of energy consumption and GHG/CAP emissions may be approximately double (Sharrard et al. 2007).

The attempts to assess the environmental impact of construction projects have been based on LCA methods and off-road equipment emission inventory models. They have enhanced the understanding of the environmental impact of construction processes by analyzing various construction projects. Still, these efforts, especially the efforts for estimating in the pre-construction stage, remain in development, and the differences in assessing methodologies generates large deviations (up to two times bigger in each air pollutant emissions) between the assessment results. Therefore, continued efforts are necessary to develop reliable estimation methodologies that can assess the environmental impacts of construction processes; these will need to be validated by measuring real-world emissions through the use of emission sensors. This data then can provide the basis for decision-making regarding the management of the

environmental impacts of construction processes.

The efforts to achieve environmentally sustainable construction processes have been implemented at different management levels: the LEED rating system and ISO 14001 certification at the environmental cooperation routine level; the Environmental Technology Verification (ETV) program at the environmental technology policy level; the NONROAD rules at the environmental regulation level; and the United States' National Clean Diesel Campaign at the environmental incentive level. Most of these efforts are focused on reducing CAP (CAC in Canada) emissions from construction equipment, since their immediate effects on human health and the environment have been relatively well-documented. Environmental regulations and environmental technology policies spur the technological development of construction equipment engines to reduce CAP emissions; environmental incentives encourage stakeholders to reduce emissions from construction equipment that is not controlled by environmental regulations. Meanwhile, efforts to reduce GHG emissions from construction processes have rarely been implemented, since GHG emissions have been recognized only recently as air pollutants that need urgent regulation. GHG emissions from construction processes are not inconsiderable compared to other industrial sources of GHG emissions; an immediate expansion of GHG emission technology policies, regulations, and incentives to levels corresponding to those for CAPs is required. In addition, current efforts have centered mostly on technological strategies such as employing diesel retrofit devices, replacing new engines and using cleaner fuels. Relatively little attention has been paid to operational strategies based on operation plan improvements for lower emissions. Such operational strategies have a great potential to reduce both GHG and CAP emissions, as well as energy consumption, with less additional cost compared to the technological strategies. For example, if robust environmental impact analysis

of construction processes is integrated into decision-making processes at the planning stage, the selection of alternative operation plans with less energy consumption and emissions are possible; this can occur while letting other aspects (time, cost, and quality) of operations stay at the same or at a slightly higher level.

CHAPTER 3

ENVIRONMENTAL PERFORMANCE OF CONSTRUCTION OPERATIONS AND ITS MANAGEMENT FRAMEWORK

1. INTRODUCTION

As summarized in the previous chapter, construction activities account for a significant amount of environmental impact. Environmental performance is therefore one of the key objectives of construction projects, along with cost, time, quality, and safety. However, the environmental aspects of construction projects are not adequately considered in current practice during the stages of a construction project—contracting, planning, and construction. Nor are we yet fully aware of what is required to reduce the environmental impact of construction operations at each stage.

In this context, this chapter describes key factors that determine the environmental performance of construction operations and strategies to improve each determinant. By integrating those strategies, the framework for the environmental performance management is presented at the end.

2. ENVIRONMENTAL PERFORMANCE OF CONSTRUCTION OPERATIONS

Environmental performance is defined as “measurable results of the environmental management system related to an organization’s control of its environmental aspects, based on its environmental policy, objectives and targets” (ISO 14001:2004). Therefore, the management of environmental performance requires defining metrics to quantify the environmental aspects of an

organization (or a project), setting performance targets with predefined metrics, monitoring metrics, and evaluating performance based on targets.

One of key performance indicators for assessing the environmental performance of construction operations in terms of energy consumption and air pollutant generation is pollutant productivity, which is production per pollutant. For example, carbon productivity, which is production per ton of carbon emissions, is a widely used metric for comparing the environmental performance between countries and industries (Kaya and Yokobori 1993; McKinsey Global Institute 2008). Pollutant productivity in construction operations can be formulated using the following equation:

$$Pollutant\ Productivity = \frac{Production}{Pollutant} = \frac{Production}{Energy} \times \frac{Energy}{Fuel} \times \frac{Fuel}{Pollutant} \quad (1)$$

When using properties of each resource utilized in construction operations, the above equation can be rewritten as:

$$P = \sum_{i=resource} f(OE_i, FE_i, EI_i) \quad (2)$$

where P is the pollutant productivity of construction operations (production/pollutant); OE_i is the operational efficiency of each resource, defined as the amount of production made by a resource per unit of energy usage of that resource (production/energy); FE_i is the fuel efficiency of each resource, measured by the amount of energy generated by a resource per unit of fuel that that resource consumes (energy/fuel), and EI_i is the emission intensity of fuel used in each resource, measured by the amount of a pollutant emitted per unit of fuel consumed (pollutant/fuel). Note that Equation (2) is an inverse form of the *fuel/pollutant* determinant of Equation (1).

The emission intensity of fuel (EI) represents the cleanliness of the fuel each resource consumes, so this property can be improved with cleaner fuels such as biodiesel and ultra-low

sulfur diesel. The fuel efficiency of resources (FE) indicates the mechanical energy conversion efficiency of equipment used in a project, so the property can be enhanced with the use of newer equipment or hybrid equipment. The operational efficiency of a process (OE) represents how efficiently given resources have been utilized for the production, so this property is closely related to traditional resource planning and scheduling. Therefore, the fuel efficiency of resources (FE) and the emission intensity of fuel (EI) values are hardly controllable once the construction phase starts, and the operational efficiency would be the only controllable determinant during construction.

3. STRATEGIES TO IMPROVE THE ENVIRONMENTAL PERFORMANCE

The strategies to improve the environmental performance of construction projects are largely twofold: technological strategies that enhance the fuel efficiency of resources and the emission intensity of fuel, and operational strategies that control the operational efficiency of construction.

3.1. Technological Strategies

Technological strategies include upgrading an existing equipment fleet to a cleaner one, utilizing retrofit technologies, and using cleaner fuel. Replacing older diesel equipment with newer equipment significantly reduces all types of air pollutants emitted by the equipment used, since newer equipment is usually manufactured under more stringent regulations (e.g. Tier 3 and Tier 4) on emission rates. Repairing, rebuilding, or replacing an engine would be a cost-effective strategy when a vehicle has a long, useful life, and when the cost of the engine is lower than the cost of all of the equipment. In addition, diesel retrofit devices for after-treatment pollution control can be installed on new or existing equipment to reduce air pollutants. For example, diesel oxidation catalysts (DOCs) and Diesel particulate filters (DPFs) can greatly reduce PM, HC, and CO emissions (EPA CAAAC 2006). Selective Catalytic Reduction (SCR) is also an

available option to reduce NO_x emissions. Lastly, switching to cleaner fuels that ensure fewer emissions would also be a great cost-effective option to take into consideration. Ultra-low sulfur diesel (ULSD), which contains lower levels of sulfur, is widely adopted to reduce PM and enhance the effectiveness of retrofit technologies (EPA CAAAC 2006). Biodiesel, which is manufactured from new and used vegetable oils and animal fats, reduces most air pollutants, including CO₂ emissions, from the life cycle perspective.

Although these technological strategies can enhance the fuel efficiency of resources (FE) and the emission intensity of fuel (EI), and can significantly impact the overall environmental performance of construction operations, the implementation of these technological strategies usually requires a great up-front cost; thus, implementation would be difficult for improving the pollutant productivity of a single project. This means that the fuel efficiency of resources and the emission intensity of fuel are mostly related to the legacy equipment fleets that contractors have. Therefore, the green capabilities of contractors that enable their construction operation to use less energy and generate fewer emissions can be evaluated based on the environmental properties (fuel efficiency, emission rate) of their legacy equipment fleet. In addition, a great up-front cost for implementing technological strategies requires a mechanism to compensate contractors' investment in upgrading their legacy equipment fleet, in order to motivate contractors' green efforts.

3.2. Operational Strategies and Operating Equipment Efficiency

Controlling the operational efficiency is the most important and *only* strategy for improving the environmental performance during construction, since other determinants of environmental performance are hardly controllable once construction starts. The operational efficiency of a

construction operation is closely related to the utilization rate of each resource employed in that operation. However, the general definition of equipment utilization rate is not appropriate as a metric to assess the pollutant productivity for two reasons. First, the equipment utilization rate is usually evaluated based on the total time available for production, in other words, the total time that equipment is on-site. But the period in which equipment is not consuming energy—that is, when the equipment is not operating but is still on-site—does not need to be accounted for in order to evaluate the pollutant productivity. Second, the equipment utilization rate generally considers the total time that equipment is involved in a production cycle to be the time that the equipment is utilized; the times that equipment is involved in the production cycle but does not perform the actual physical work should be differentiated in accounting the pollutant productivity. For example, the time during which an excavator waits for the exchange of trucks should be considered as non-valuable operating time, since an excavator still consumes energy but does not carry out any physical work. Further, the length of that period can be controlled by better work-flow management and resource allocation. Therefore, as a metric to represent the pollutant productivity of the use of a single piece of equipment, we define Operating Equipment Efficiency (OEE) as:

$$\text{Operating Equipment Efficiency (OEE)} = \frac{\text{Valuable Operating Time}}{\text{Total Operating Time}} \quad (3)$$

where Total Operating Time is the time that equipment is available and operating, and Valuable Operating Time is the time that equipment performs any physical work to complete its job.

Figure 3.1 summarizes the computation procedure of OEE. In addition, we can see that the OEE computation procedure is different from the one for job efficiency (i.e., total operating time/on-site standing time), as discussed earlier.

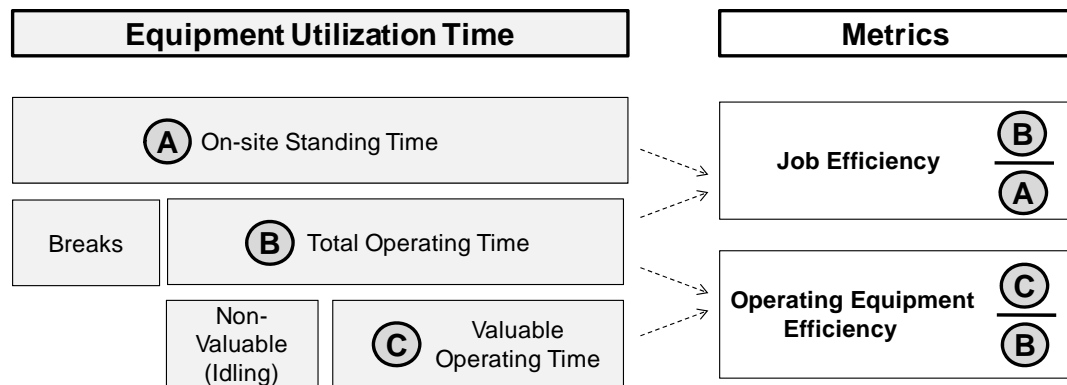


Figure 3.1. Definition of Operating Equipment Efficiency (adapted from Nakajima 1988)

The OEE of construction equipment in typical construction operations greatly varies, but is not high. For example, Komatsu excavators in Colorado and Wyoming are idling approximately 35% of the time (Hagerty 2011), which means an OEE of 65%. In a project located in an urban area, the OEE of construction equipment is much lower due to the density of the jobsite and traffic delays. In the urban underground project that will be introduced in the case study section, it was observed that excavators employed in the operations have an OEE of around 30% to 40%. This indicates that there are great opportunities to improve OEEs in construction operations, and to enhance the environmental performance.

The control of OEEs is closely related to traditional process management that pursues maximizing the utilization of resources, but has different performance metrics than traditional process management that focuses on production rate and cost. Therefore, the implementation of operational strategies that pursue the enhancement of OEEs and environmental performance requires methods and tools that predict and monitor relevant metrics (OEEs and air pollutants) based on given resource allocation and schedules.

4. MANAGEMENT FRAMEWORK

In the previous section, the requirements for implementing technological and operational strategies are discussed. Based on the requirements, the framework that enables construction stakeholders to manage the environmental performance of construction operations is presented as Figure 3.2.

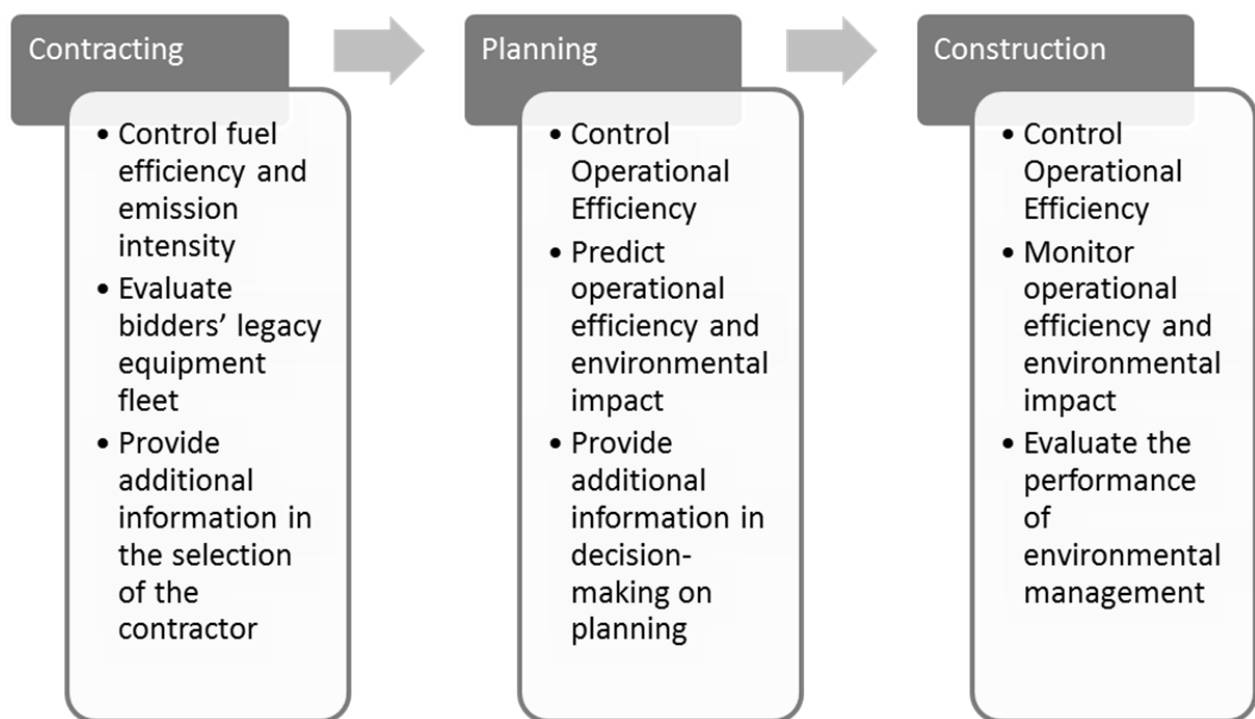


Figure 3.2. The management framework of environmental performance

At the bidding and contracting stage, the green capabilities of contractors are evaluated based on the environmental properties of their legacy equipment fleet. Clients can select a greener contractor based on such evaluations. The selection process that includes the evaluation of green capabilities can work as the mechanism to compensate contractors' efforts in upgrading their legacy equipment fleets. Once the contractor is selected, the focus of the management is

shifted to the operational efficiency. At the planning stage, the additional environmental impact caused by the operational inefficiency of the process is assessed. Management actions (e.g. change in operational settings, task orders) usually generate a change in the OEE of each piece of equipment. By using the process model (e.g. discrete-event simulation), we can predict such a change in OEE and evaluate the amount of environmental impact caused by that predicted change. This helps the identification of plausible options among various alternatives, provides additional information on the environmental impact of options in decision-making, and helps to set the targets on both the OEEs and the environmental impact level. At the construction stage, the OEE of each piece of equipment is monitored and interpreted into environmental impact data (e.g. energy usage, air pollutants). Tracking the usage and OEEs of equipment allows the calculation of the amount of air pollutants emitted from an equipment fleet used for construction operations, using the emission factor database of construction equipment. The performance of the environmental management activities can be evaluated by comparing the OEE and environmental impact level that are tracked in daily construction with the target values that are set at the planning stage. Figure 3.3 details the evaluation of environmental performance based on the target OEE and environmental impact level.

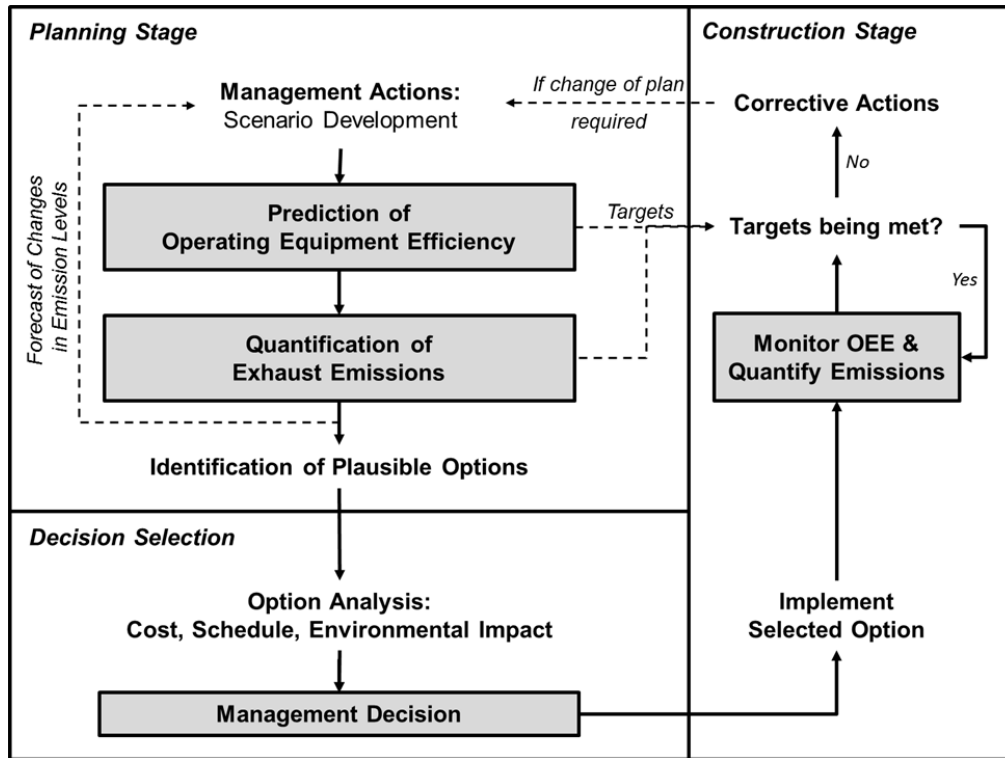


Figure 3.3. Identification of management target and evaluation of performance

5. CONCLUSIONS

In this chapter, the environmental performance is formulated as a function of the operational efficiency of a process, along with the environmental properties of resources used and fuel consumed (the fuel efficiency of a resource and the emission intensity of fuel). The technological strategies that enhance the environmental properties of resources and fuel are described, as are the operational strategies that control the operational efficiencies. In addition, the requirements for their implementations are discussed. Based on the requirements, the management framework that encompasses the contracting, planning, and monitoring stages of construction projects is presented and discussed. The following chapters will present each module in detail.

CHAPTER 4

THE EVALUATION OF GREEN CAPABILITIES OF CONTRACTORS

1. INTRODUCTION

Contractors could mitigate emissions by replacing old equipment with pieces that are new and energy-efficient, as well as by using cleaner fuels. By reducing transportation loads, the reduction of waste and the use of locally manufactured/supplied materials could further contribute to the decrease of emission levels. However, voluntary innovation by contractors on this issue is rare since the costs involved with improving the environmental performance of equipment outweigh the short-term benefits. In this context, some types of incentives are required to stimulate contractors' green efforts. Giving a bidding preference to a *green* contractor during the evaluation of bids would be a cost-effective incentive for spurring on the innovation of contractors.

With that said, this chapter discusses including the environmental cost of construction emissions as a criterion in new contracting methods in order to encourage contractors to undertake efforts to reduce emissions that arise from their activities. The methodology to evaluate the *green* efforts of bidders in the proposed contracting methods will be also presented.

2. ENVIRONMENTAL CONSIDERATIONS IN CONSTRUCTION CONTRACTING

The environmental impact of construction activities has been widely contemplated in construction contracting, in the form of contract specifications, contract allowances, and bidding preferences (Cui and Zhu 2011). Contract specifications require contractors and subcontractors

to use construction equipment certified by EPA, or to install diesel emission retrofit devices, such as diesel oxidation catalysts (DOCs) and diesel particulate filters (DPFs). Such contract specifications are found in several public projects, such as the Central Artery project undertaken by the Massachusetts Highway Department, the Dan Ryan Expressway project undertaken by the Illinois DOT, and in every contract put forward by the New York Metropolitan Transportation Agency (EPA 2011). These types of contract specifications do not directly affect the selection of contractors in the bidding evaluation process, while they can potentially limit bid participation from small contracting companies that may lack the financial wherewithal to upgrade equipment and purchase emission control devices (ICF 2005). Contract allowances reimburse part or all of the initial purchase cost of green equipment and technologies, in order to spur contractors' use of cleaner construction equipment. For example, Texas DOT Special Specification 5018 provides an incentive to contractors who use cleaner engines and fuels on roadway and maintenance projects, based on two factors, namely, engine horsepower and operation time of equipment on site (Cui and Zhu 2011). However, the use of bidding preferences that provides advantages to a green contractor in bidding evaluation has rarely been found.

In contrast to the efforts on mitigating diesel emissions delineated above, the GHG emissions and energy consumption from construction processes have rarely been a concern in contracting processes (ICF 2008). A handful of transportation agencies, such as the New York State Department of Transportation (NYSDOT) and the Metropolitan Transportation Commission in the San Francisco Bay Area, have considered the importance of mitigating construction emissions in the planning phase, addressing the issue through environmental impact assessment reports (ICF 2008). In these cases, these analyses are used to compare overall energy consumption between “No-Build” and “Build” alternatives, rather than to identify mitigation

opportunities for construction GHG emissions. Yet the emission intensity for transportation facility construction is considerable, and transportation agencies will need to identify mitigation opportunities more vigorously in the future. The proposed bidding methods, by encouraging contractors to compete regarding GHG emission reduction, would thus involve contractors in identifying cost-effective mitigation opportunities.

3. EVALUATION OF GREEN CAPABILITIES OF CONTRACTORS IN CONSTRUCTION CONTRACTING

The contractor's capability to perform green construction has not been considered in traditional contract and bid evaluation practices. Contractors are unlikely to voluntarily improve their capability (e.g. newer equipment, retrofitting, cleaner fuel). The criteria to evaluate green capabilities of contractors therefore need to be included in the bid evaluation process to realize effective change. This line of thought is supported by the success of the A+B bidding method, which includes time in the low bid determination, to reduce schedules. We thus suggest an A (cost) + C (environmental cost) and/or an A (cost) + B (time) + C (environmental cost) bidding method; each includes the environmental cost caused by construction-related activities in the bid evaluation.

3.1. Success of the A+B bidding method

In order to rectify disadvantages in conventional competitive bidding systems in which a contractor is selected based only on a cost evaluation, various alternate contracting methods (ACMs) have been suggested and recently implemented. The A+B method, for example, which is also referred to as cost-plus-time bidding, has been utilized increasingly to accelerate project completion in highway construction (Anderson and Damnjanovic 2008). Within this system, each bidder is required to bid on two components: the total construction cost (A) and the total

number of days necessary to complete the project (B). The lowest combined bid is calculated with the following formula:

$$\text{Bid award cost} = A + (B \times \text{Road User Cost})$$

In this formula, A = the cost estimate in dollars, B = the time estimate in days, and the Road User Cost = the daily road user cost in dollars per day.

The road user cost (RUC) represents the increased operating costs incurred by traffic delays (time and distance) and agency costs (inspection and traffic control), and is calculated by the owners, which are usually state highway agencies. As stated, the winning bid in the A+B method is determined by a combination of the A and B components. However, the cost reimbursement awarded to the winning contractor is determined based solely on the amount of the A bid. Incentive/disincentive (I/D) provisions are also usually included in this bidding system to ensure that the completion date is attained and to encourage a further reduction in the actual time required for construction.

According to the Federal Highway Administration's (FHWA) report on ACMS (Anderson and Damnjanovic 2008), 26 out of 30 responding STAs have used the A+B bidding system, and 13 have utilized the method more than 10 times. Further, 60% of the respondents stated that the A+B bidding method affected a 5% or greater reduction in project duration. A comprehensive evaluation of A+B contracting practices in Minnesota between 2000 and 2005 (MnDOT 2006) indicated a 15% reduction in estimated construction time when the time bid of the low combined bidder was compared to the maximum schedule estimate of the MnDOT. Further, an 11% additional reduction was reported once actual construction time was compared to the low time bid plus extensions. No notable adverse effect on cost or quality has been reported when the A+B method has been utilized (Ellis et al. 2007).

Surprisingly, the actual impact of the time component in determining the lowest combined bid of the A+B bidding system is not that significant. In 90 out of 120 NYSDOT contracts wherein the A+B bidding method was used, the lowest cost (A) bidder became the lowest combined bidder (even though it was not the shortest time (B) bidder in some cases) and was awarded the contract (Kent 2003). In only 30 out of 120 contracts, the combined lowest bidder did not have the lowest cost bid but did have the shortest time bid. Furthermore, within these 30 bids, the difference between the lowest cost (A) bids and the cost (A) bids of the successful contractors (who had shorter time (B) bids but higher cost (A) bids) was typically small: less than 1% of the cost bid of the successful contractors (Kent 2003). This indicates that a success of the A+B bidding system in encouraging contractors to reduce completion times is seemingly connected to other motivational factors of a multi-parameter bidding system, rather than relying on the actual impact of the time (B) bid in determining the lowest combined bidder. The most important factor of the A+B bidding system that enables its success is that the categorization of time as a bid component results in competition between contractors. In order to remain competitive among other bidders, contractors are forced to reduce construction time at the lowest cost. As a result, contractors' estimates concerning project duration tend to fall in comparison to the initial calculations of departmental engineers in most A+B bidding contracts (Ellis et al. 2007). This means that the use of the secondary factor does not increase the cost of the project but offers an incentive to contractors to be more competitive in those secondary factors.

4. COST + ENVIRONMENTAL COST (A+C) AND COST + TIME + ENVIRONMENTAL COST (A+B+C)

BIDDING METHODS

The proposed A+C and A+B+C bidding methods are based on the idea of the aforementioned multi-parameter bidding system. In this type of bidding system, the winner is selected based on the combined dollar value of multiple components. In the A+C and A+B+C systems, bidders are required to bid on an additional C component that represents the environmental cost caused by their estimated construction energy use and emissions. The A+C method adds this C component to the conventional cost (A) bidding process. The A+B+C system in turn modifies the A+B bidding method by adding a C component. The winning contractor will thus submit the lowest total combined bid, which is calculated with the following formula:

$$\text{Bid award cost} = A + \{B \times \text{Road User Cost}\} + C$$

In this formula, A = the cost estimate in dollars, B = the time estimate in days, Road User Cost = the daily road user cost in dollars per day, and C = the estimated environmental cost. $\{B \times \text{Road User Cost}\}$ is included only in the A+B+C bidding method.

As with the A+B bidding method, the A bid will be the sole determinant for the base cost reimbursement awarded to the winning contractor. Incentive/disincentive provisions should also then be included in the A+C and A+B+C bidding methods to ensure compliance with targets for the emission levels permitted by the contract, and to encourage further reductions.

The C bid (the environmental cost) is defined based on the concept of the eco-costs (Vogtländer et al. 2001), and is calculated with the following formula:

$$C (\text{environmental cost}) = \Sigma (\text{emission estimate} \times \text{eco-cost of emission}) + \Sigma (\text{fossil fuel use} \times \text{eco-cost of material depletion})$$

The environmental cost is determined by combining the environmental cost of emission

generation (the amount of each emission generated by construction activities multiplied by the eco-cost of each emission) and the environmental cost of energy use (the amount of fossil-fuel consumed multiplied by the material depletion eco-cost of the fossil fuel used). The following section discusses how the C bid of each contractor can be calculated. It also contains a detailed discussion of how eco-cost is determined.

4.1. Environmental assessment of a construction project

In order to determine the C bid, bidders are required to assess the environmental impact that will be caused by their construction activities, such as air pollutant emissions and energy consumption. The environmental assessment of a construction project can be performed with life-cycle assessment (LCA), such as a process-based or an input-output approach.

For A+B and A+B+C bidding methods, a process-based approach is recommended because it ensures better accountability of environmental impact assessment of construction plans (equipment fleet, fuel, and material source selections) of bidders, and thereby permits bidders to benefit from any improvements regarding their green capabilities. An input-output approach, in contrast, tends to provide average estimates that are based on past projects and do not consider the selection of construction methods and equipment.

The scope of the environmental impact assessment, especially when a process-based approach is chosen, also needs to be carefully defined at the bid letting stage; environmental impact estimates could otherwise vary greatly. This will be closely connected with project delivery methods (e.g., design-bid-build or design-build). In the case of design-bid-build projects, there would generally be no significant difference in the environmental impact related to the material use between the bidders. Then the scope of environmental impact assessment includes only direct emissions generated by on-site equipment operation and transportation (from final

suppliers to the construction site). On the other hand, design-build projects require the inclusion of the environmental impact related to the material use of each bidder (e.g. recycled material, pavement type) in the assessment boundary.

4.2. Environmental cost calculation in the A+C and A+B+C bidding methods

For the implementation of the A+C and A+B+C bidding methods, the result of the environmental impact assessment of bidders needs to be expressed in a single monetary value. There are a number of impact assessment methods that interpret the LCA result and provide an LCA-based single indicator, for example, Eco-indicator 99 (Goedkoop et al. 1999) and Life Cycle Assessment- An Operational Guide to the ISO Standards 2001 (CML2001) (Guinee et al. 2001). In this chapter, we chose the eco-costs proposed by Vogtländer et al. (2009), because (1) the eco-costs are expressed in a standardized monetary value that can be easily understood and (2) the calculation is transparent, compared to damage-based model that involves complex calculation with subjective weighting of the various aspects contributing to the overall environmental burden (Bengtsson and Steen 2000; Finnveden 2000). Table 4.1 summarizes the eco-costs of emissions and material depletion related to construction activities.

Table 4.1. Eco-costs of emissions and material depletion (Vogtländer et al. 2009)

	Eco-costs	
	(€/kg)	(\$/kg) ¹
Emissions		
CO ₂	0.135	0.1755
CO	0.24	0.312
SO ₂	7.55	9.815
NO _x	5.29	6.877
PM _{2.5}	27.44	35.672
VOC	3.54	4.602
Material Depletion		
Diesel	0.7	0.91
Petrol	0.7	0.91
¹ calculated with the currency rate of € 1 = \$ 1.3 as of Dec 27, 2011		

5. CASE STUDY

To illustrate the proposed bidding system, a hypothetical case study for the A+C bidding method was developed based on the LCA case study of Cass and Mukherjee (2011) and its actual bidding information. The chosen project is a pavement rehabilitation and re-construction project of a 7-mile four-lane road in the state of Michigan. Cass and Mukherjee (2011) quantified the environmental impact from construction equipment use, transportation, material manufacturing, equipment manufacturing, and fuel production. Since this project was delivered by design-bid-build, this case study includes only the emissions and fuel use from construction equipment use and transportation. For the quantification of emissions from construction equipment use and transportation, Cass and Mukherjee (2011) used an emission calculator, e-CALC (Sihabuddin and Ariaratnam 2009), which is based on EPA's NONROAD model (EPA 2009c). This chapter

uses their transportation results as is. The emissions and fuel use from construction equipment, while based on Cass and Mukherjee (2011)'s input data, are recalculated with the use of EPA's NONROAD model, which allows for better testing of the impact of various fleet configurations. The total eco-costs of each emission and fuel use are then assessed based on the eco-cost indexes listed in Table 4.1.

Table 4.2. Emissions, fuel use, and their eco-costs of the case study

	CO (kg)	NO _x (kg)	PM (kg)	THC (kg)	CO ₂ (kg)	SO _x (kg)	Fuel use (kg)
On/Off-site transportation	1,961	3,490	9	340	872,148	8	273,740
On-site construction equipment	3,756	6,917	445	506	1,393,097	27	439,682
Total emissions	5,718	10,407	454	845	2,265,245	35	713,422
Total eco-costs (\$)	1,784	71,566	16,200	3,891	397,551	344	649,214

Note: 1) Emissions and fuel use are based on the study conducted by Cass and Mukherjee (2011), and the transportation results are identical.

2) Emissions and fuel use from construction equipment are based on Cass and Mukherjee's input data, but recalculated using EPA's NONROAD model. The NONROAD model allows for better testing of the impact of various fleet configurations.

3) The eco-cost is newly calculated with eco-cost index in Table 4.1. THC belongs to a larger group of VOC (EPA 2010b), so the eco-cost of VOC is applied.

Table 4.2 summarizes the amount of emissions, fuel consumption, and their eco-costs. The construction equipment use and on/off-site transportation in the case project are estimated to consume around 713 metric tons of fossil-fuel (diesel), and to generate 2264 metric tons of CO₂ emissions and 18 metric tons of NO_x emissions. The total eco-cost corresponding to those amounts of fuel use and emissions is found to be around 1.14 million dollars. The material depletion eco-cost of fuel consumption is higher than aggregated emission eco-costs, and the eco-cost of CO₂ emissions accounts for around 80% of aggregated emission eco-costs and 35% of total eco-costs.

5.1. Mitigation options

There are many options that bidders could have adopted to reduce their fuel consumption and emissions in the case project. The impact of such mitigation options to the C bid (total eco-costs) is evaluated in this section in order to examine the magnitude of bidding preference that the adoption of the mitigation options can have in the proposed bidding system. Figure 4.1 illustrates the change to the environmental cost (total eco-costs) by the adoption of different mitigation options. It is assumed that the contractor can control the fleet configuration of his/her construction equipment, but cannot control transportation vehicles that generally belong to material suppliers.

- Replacement of old equipment to newer equipment: as discussed earlier, newer equipment is manufactured under more stringent emission standards mandated by the EPA. For example, the NO_x emission rate of a “Tier 3” excavator is 50% of that of a “Tier 1” excavator with the same engine size. Cass and Mukherjee (2011) assumed that the model year of all the equipment used in the case project was 2008, and determined the tier information of equipment accordingly. But this assumption is quite optimistic, as they mentioned in their paper. Therefore, we assumed that all the equipment used in the base scenario is “Tier 1,” and evaluated the reduction of total eco-costs in the cases that all the equipment used is “Tier 3” and “Tier 4”; a “Tier 4” scenario (equipment manufactured after 2011) is not realistic for this project, but is tested for future reference. The total eco-costs of the “Tier 3” and “Tier 4” scenarios are reduced by 5.7 and 7.2 percent, respectively, compared to the base scenario (“Tier 1”) (See Figure 4.1). It should be noted that the eco-cost savings in “Tier 3” and “Tier 4” scenarios would be greatly

underestimated compared to the real environmental benefits from replacing old equipment with newer equipment; EPA's NONROAD model that is used to calculate the emissions in this chapter uses fuel consumption rate and CO₂ emission rate of Tier 0 engines for all engines of different Tiers, due to lack of data (EPA 2010a). The improvement of fuel economy in newer equipment, therefore, was not reflected in this result.

- Use of retrofit devices: adding advanced pollution control devices such as a diesel oxidation catalyst (DOC), a diesel particulate matter filter (DPF) and a selective catalytic reduction (SCR) system of NO_x would reduce diesel emissions from construction equipment. The installation of a DOC can reduce PM between 20% and 50%, HC by 50%, and CO by 40% (EPA CAAAC 2006). An SCR system, which is an emerging technology for nonroad equipment that is expected to be used mostly in combination with DOC or DPF, can reduce NO_x between 70% and 90% (EPA CAAAC 2006). The use of DOC and SCR+DOC with all equipment used in the base scenario reduces the total eco-cost by 0.9% and 7.6%, respectively (See Figure 4.1).
- Use of Biodiesel (B20): The substitution of biodiesel fuels for petroleum diesel will reduce life cycle emissions for construction equipment. Still, biodiesel cannot be used in its pure form (B100) without a certain engine modification (EPA CAAAC 2006). A blend of 20% biodiesel and 80% regular diesel (B20) will reduce life-cycle energy consumption and CO₂ emissions by 9%, PM by 11.8%, and CO by 4.1%, but increase NO_x by 3.5% and HC by 1.6% (Pang et al. 2009). The use of B20 with all construction equipment saves total eco-costs 4.8% (See Figure 4.1).

- Replacement with hybrid equipment: Many manufacturers of construction machinery have recently released hybrid construction equipment. Compared to conventional construction equipment, hybrid construction equipment is known to consume around 30% less energy and generate less CO₂ emissions (Komatsu 2008). However, the impact of hybrid equipment on other emissions is still unknown. In this case study, emission rates from hybrid equipment of other air pollutants are assumed to meet the Tier 3 standards. This scenario has 21.8% lower eco-costs compared to the base-scenario.
- Change of material sources: Using nearer material sources will reduce overall emissions and fuel use generated from material transportation. In the case project, the transportation of concrete generated the highest emissions among 16 items of material delivered, and concrete was delivered from two different plants; one was 14.2 miles from the job site, the other was 26.3 miles. When assuming that all of the concrete is sourced from the nearer plant, the eco-costs are reduced by 5.5%. In the case that all aggregate is also sourced from the nearer pit (between the two different pits used), the eco-costs are reduced by 11.2%

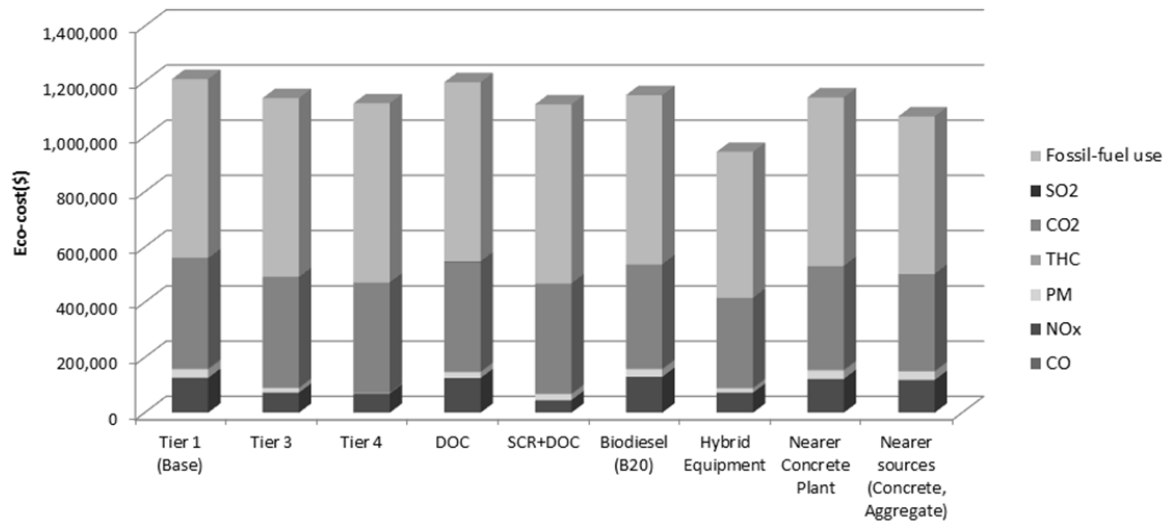


Figure 4.1. Comparison of total eco-costs between mitigation options

5.2. Bidding Preference in the A+C bidding method

The effect in the A+C bidding process of various mitigation options upon the bid gap is explored further in Figure 4.2. The bidding preference featured in Figure 4.2 indicates the percentage of the A bid gap that a bidder can gain by adopting mitigation options against another bidder who does not have any mitigation plan (i.e., who stays with the base scenario); the A bids of those two bidders are assumed to be identical to the actual awarded cost of this case project, which is around 21 million dollars. For example, a bidder who plans to use hybrid equipment will have the same combined bids with another bidder who has a 1.21% lower A bid but does not have any mitigation plan. This result illustrates that the green efforts of bidders can be a critical factor when determining the bid result in the A+C bidding method. In particular, when the A bid gap between bidders is below 1%, introducing mitigation measures would significantly impact the determination of the winning bidder. Considering the success story of the A+B bidding method,

this level of C bid impact is expected to create competition among bidders on the secondary bid criteria under a multi-criteria bidding system.

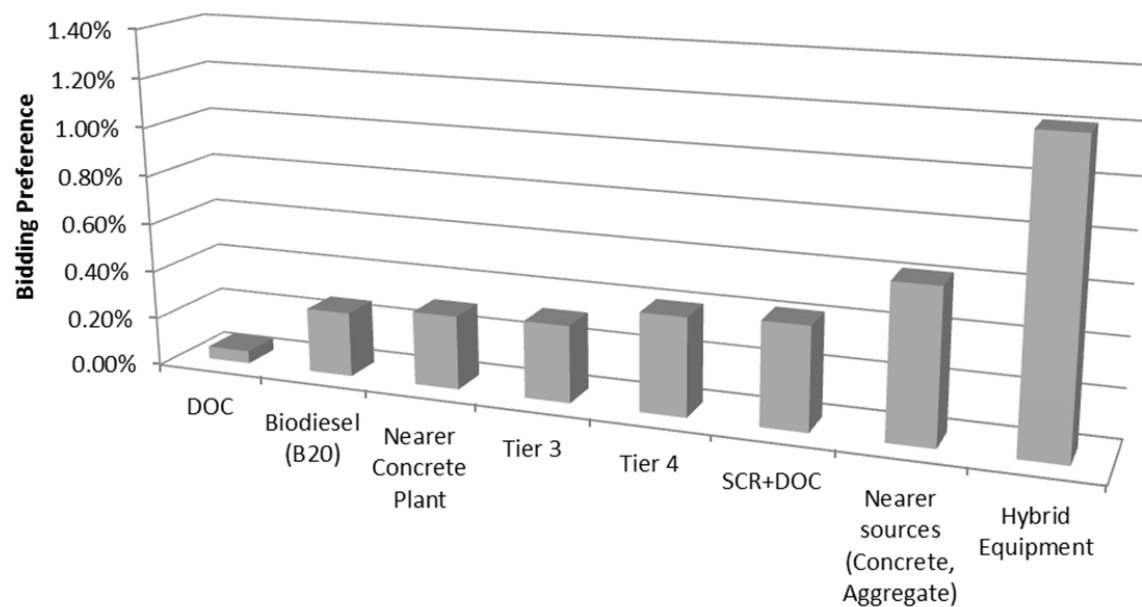


Figure 4.2. Change of the bidding preference by adopting each mitigation measure in the case study

5.3. Simulated bid tabulation

Table 4.3 illustrates the simulated bid tabulation using the A+C bidding method. The A bids (construction cost) of bidders are based on the actual bid tabulation of the case project (Michigan DOT 2009). Bidders are assumed to have different mitigation strategies for their construction emission and energy use. For example, Bidder Y is assumed to use hybrid equipment, Bidder Z is assumed to use SCR+DCR for all construction vehicles, and Bidder W is assumed to use B20 instead of petroleum diesel, while the lowest bidder for the A bid (Bidder X) is assumed to have no mitigation plan.

Any possible cost increase due to bidders' introduction of mitigation plans is not

considered in this simulation bid tabulation. In fact, upgrading legacy equipment fleets (including the installment of retrofit devices) requires a significant but one-time cost for contractors. It is then likely that bidders spread that one-time additional cost over several projects based on the service time of the equipment. Therefore, it is uncertain what incremental cost bidders will put on their A bid in order to get reimbursed for their investment on green practices, but this needs to be examined by future research efforts.

Table 4.3. Bid Tabulation Using A+C Bidding Method

Bidder	Construction cost (A) (\$) – (rank)	Bid gap with the lowest bid (\$)	Submitted Mitigation plan	Environmental cost (C) (\$)	Total combined bid (A+C) (\$) – (rank)	Bid gap with the lowest bid (\$)
X	21,735,224 (1)	0	None	1,208,498	22,943,722 (1)	0
Y	23,368,422 (2)	1,633,199	Hybrid Equip.	945,424	24,313,846 (2)	1,370,125
Z	23,730,070 (3)	1,994,846	SCR+DOC	1,116,990	24,847,061 (3)	1,903,339
W	25,475,759 (4)	3,740,535	B20	1,150,502	26,626,261 (4)	3,682,539

Notes: 1) “A” bid tabulation is based on the actual bid tabulation of the case project (Michigan DOT 2009) and does not include any possible cost increase due to the mitigation plans.

When the bidding system shifts from the traditional to the A+C method, Bidders Y, Z, and W can reduce the final bid gap between themselves and the lowest bidder (Bidder X). In this case study, the gap between the A bids of Bidder X and other bidders was higher than 7%, so the green efforts of bidders cannot reverse the final bid result in the A+C bidding system. However, in the scenario in which the gap between the A bids of the lowest bidder and other bidders is smaller, the second lowest bidder in the traditional bidding method could have a chance to be awarded the bid in the A+C bidding method.

5.4. The impact of environmental cost index on bidding preference

The monetary values that represent the environmental impact of air pollutants and resource depletion are strikingly different, based on their impact assessment method and locality. Most

methods to calculate a “single indicator” are based on *damage costs*, also referred to as *external costs*. This is the monetary value assigned to the damage caused by a unit of emission or material use. The eco-costs, though, are based on *prevention costs*, also referred to as *abatement costs*. These are the costs required to reduce emissions to a sustainable level in a certain region (e.g. the European Union) with the best available measures. For example, the prevention cost of CO₂ is the cost of replacing coal-fired power plants with windmill parks at the sea. One drawback of using eco-costs is that they have been calculated for situations in the European Union.

Therefore, this section examines the impact on the bidding preferences of using other impact assessment methods developed for the United States. Also, the difference of using *damage costs* and *prevention costs* is examined. Wang et al. (1994) provides estimates of the damage costs and preventive costs of air pollutants in 17 U.S. regions. They developed regression models to estimate the monetary values of air pollutants by population and air quality of the region, based on previous studies on environmental valuation. Although Wang et al. (1994)’s results have some drawbacks due to outdated data sources and no estimate on material depletion impact, the analysis using Wang et al. (1994)’s estimates provides a preliminary result of the impact of using different environmental cost indices on the bidding preference under the A+C bidding method.

The scenarios using the values of the most and least popular areas in their study are presented here, since any region around the case project is not included in this study. High-cost scenarios are based on the monetary values of air pollutants in Los Angeles, while low-cost scenarios are based on the monetary values of air pollutants in Las Vegas. In addition, monetary values of CO₂ are based on other recent studies that are widely accepted, since the monetary values of CO₂ are less affected by locality. Table 4.4 summarizes the monetary values of air

pollutants that are used in this analysis.

Table 4.4. Damage cost and preventive cost of air pollutants in U.S. regions (Wang et al. 1994)

	Damage Cost (\$/kg)		Prevention Cost (\$/kg)	
	High	Low	High	Low
CO	0.519	0.519	8.370	4.792
SO ₂	6.868	3.823	23.320	20.155
NO _x	16.954	1.574	37.800	9.031
PM _{2.5}	29.756	4.240	10.484	7.249
VOC	8.840	0.553	33.303	8.823
CO ₂	0.106 ¹	0.106 ¹	0.176 ²	0.176 ²
Material Depletion	N/A	N/A	N/A	N/A

¹based on Stern (2007); ²based on Vogtländer et al. (2009)

Figure 4.3 illustrates the bidding preference using the different monetary values of air pollutants. It should be noted that the environmental cost of material depletion is not taken into consideration in the analysis, since Wang et al. (1994)'s model does not include an environmental impact assessment on material depletion. It is found that the level of bidding preferences that a bidder can gain by adopting mitigation measures is greatly elevated in high dense regions that have a higher environmental cost index of air pollutants. In such regions, mitigating diesel exhaust emissions other than GHG emissions is a more effective way for bidders to gain a higher bidding preference. For example, under high damage cost and high preventive cost scenarios, using SCR+DOC that does not have any impact on GHG emissions provides a higher bidder preference than using hybrid equipment.

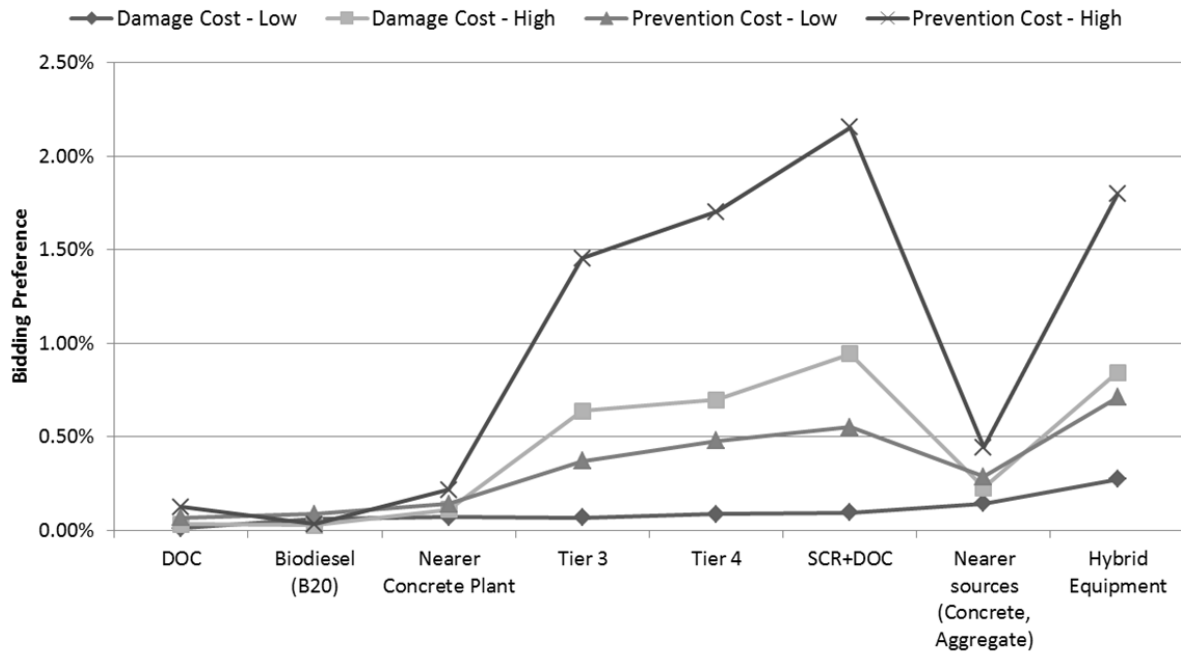


Figure 4.3. Bidding preference in the case study with different environmental cost indices

6. DISCUSSION

Giving the bidding preference to greener contractors has several advantages over contract specifications and contract allowances. First, the provision of bidding preferences still offers opportunities for bid participation from small contracting companies that do not have the financial capability to implement green plans but do have good cost competitiveness; contract specifications may limit bid participation from such companies. In addition, the bidding preference to be provided under the A+C bidding method will be proportionate to the actual absolute amount of emission reduction to be achieved. The effectiveness of additional cost investment for emission reduction is guaranteed with the provision of bidding preferences; the amount of emission reduction to be achieved under contract specifications is uncertain until the completion of a project. Last but not least, the provision of the bidding preferences will let

bidders compete on the cost-effectiveness of their mitigation plans, as we have observed in the practices of the A+B bidding method. The owner, therefore, will achieve greener construction practices with a minimum increase in cost. This way of paying the additional expense of green construction is more reasonable than contract allowances or some type of contract specifications, wherein the owner is required to reimburse the incremental costs incurred by a contractor's green practices.

Thus far, however, without regulations, private owners lack significant motivation to seek greener contractors because of the added cost in doing so. In contrast, public entities have expressed great interest in and moved toward attracting greener contractors, utilizing various subsidy and incentive programs to indirectly pursue reductions in emissions, as described in Chapter 2. Current and future regulatory actions require public entities to inventory their GHG emissions, set the reduction target, and build the mitigation plans to meet that target (White House 2009). The GHG emissions generated by construction work largely contribute to the GHG inventory of some public entities, such as DOTs. Thus the application of the A+C and A+B+C bidding methods will most likely draw the interest of public entities, where they can contribute to and accelerate on-going efforts to mitigate energy use and emissions. Transportation projects in particular, such as road and bridge construction, could incorporate and greatly benefit from A+C and A+B+C bidding methods due to their relatively high emission intensities. Projects to reconstruct or rehabilitate transportation facilities that use the A+B bidding method could also benefit from a shift to the A+B+C system. Public owners could then pursue further mitigation of energy use and emissions by incorporating the traffic emissions generated by delays and detours resulting from road construction in the A+B+C bidding method. Current road user cost calculations used in the A+B bidding method include only vehicle operating and time costs

resulting from traffic delays and detours, and do not include the additional costs of GHG emissions resulting from traffic delays and detours (NJDOT 2001).

Contractors would benefit from the adoption of A+C and A+B+C bidding methods. Voluntary and regulatory GHG emission reporting programs, client preferences for green products, fossil fuel price increases, and environmental legislation will each force contractors to reduce their energy use and emissions. Within the A+C and A+B+C bidding methods, however, they will not be forced to adhere to specific mitigation strategies; instead, they will be able to create and adapt innovative means to mitigate construction emissions and energy use. Successful strategies to reduce energy use and emissions would then enhance the competitiveness of a given contractor and increase his/her chance of winning a bid within the A+C and A+B+C systems. The potential approaches toward emission reduction in construction are extremely diverse; attempts to restrict them within contract specification would be counterproductive. Some reduction is possible within the traditional approach, of course—replacing old equipment with pieces that are newer and cleaner, and shifting to cleaner fuel will reduce emissions in construction. However, a much more drastic reduction could be accomplished through the design of more energy-efficient construction processes and methods. The A+C and A+B+C bidding methods provide the flexibility necessary to allow for innovation, and could lead to profound mitigation strategies within contracting and construction procedures. In addition to the A+C and A+B+C bidding methods, public owners should consider Performance Contracting for Construction (PCfC), which the FHWA has developed and is promoting (SAIC 2009); this would further incorporate construction emissions into contracting procedures. PCfC suggests defining a set of performance goals that a contractor must meet, with measurement methodologies in place to evaluate the performance of the contractor regarding each goal. In

order to incorporate emissions in PCfC, the mitigation of construction emissions needs to be a performance goal. The contractor's performance toward the goal of emission reduction can then be evaluated to determine whether the contract has been fulfilled. The mitigation of construction emissions has yet to be set as a performance goal within a PCfC pilot project, however; in contrast, other environmental impacts, such as construction noise and material recycling/reuse, have been included. To pursue the mitigation of construction emissions within PCfC, performance measures need to be defined according to the level of reduction from the construction emission baseline desired. The baseline can be defined using construction quantification methods. Setting performance goals to mitigate construction emissions would not only achieve the desired levels of construction emissions, but would also affect bid evaluation processes within the best value award system of PCfC.

7. RECOMMENDATIONS FOR FUTURE IMPLEMENTATION

Several challenging issues remain in the implementation of the A+C and A+B+C bidding methods. The first challenge is how to ensure the implementation of promised emission mitigation plans. Current practices of *contract specifications*, which obligate contractors to use certified equipment and emission retrofit devices, provide a tangible solution to address this challenge. In these practices, public clients track construction equipment used in the project in order to ensure that any piece of diesel equipment that does not comply with the *contract specification* will not be used. If non-compliant equipment is used more than 24 hours after its identification, all payments are withheld for work performed on any items on which the non-compliant equipment was used. Likewise, public clients enforce the implementation of emission mitigation strategies promised by contractors. In addition, the monitoring of equipment usage

and operational efficiency should be combined in order to prevent the increase of emissions due to low productivity. The monitoring system to be introduced in Chapter 6 can be utilized for this purpose.

Another challenge is the burden placed on bidders to estimate construction emissions and develop their C bids, and the bidders' resistance due to this burden. In the design-bid-build projects where bidders have the same bill of quantity—bidders have the same specifications quantities of material, and mostly similar levels of required equipment operation hours—the required input data from bidders is not that great. Public entities, therefore, would reduce the burden on bidders by providing a tool to support the calculation procedures. However, in design-build projects, bidders are required to be equipped with the ability to perform such procedures by themselves.

In addition, public entities need to develop their own impact assessment method to convert emissions and energy use into a monetary value. As examined in the previous section, the environmental cost of emissions and energy use may vary with using different environmental cost indices. In the case of the A+B bidding method, public clients have their own method to estimate the road user cost that represents the monetary value of time. Likewise, the monetary values of emissions and energy use need to be updated or replaced according to the situation of a region where public entities authorize the execution of contracts.

8. CONCLUSIONS

This chapter presented the A+C and A+B+C bidding methods to address the growing social requirement to mitigate construction emissions and to discuss the benefits of these methods both to public clients and contractors; further, the challenges involved in the implementation of these

bidding systems are discussed. The case studies demonstrate that the proposed bidding methods could provide certain bidders—those with more effective plans for emission mitigation—with a higher chance of winning a bid. In fact, adopting the A+C and A+B+C bidding methods would encourage contractors to identify and quantify construction emissions, as well as develop greener construction methods.

CHAPTER 5

PREDICTIVE ASSESSMENT MODEL OF ENVIRONMENTAL PERFORMANCE

1. INTRODUCTION

Improving the operational efficiency of each resource employed in operations is the primary way to improve the environmental performance of projects (Hoffman, 2005; Tam et al. 2006; Matar et al. 2008). Pursuing better operational efficiency in complex construction operations is not simple, though; the efforts to increase the operational efficiency of one piece of equipment often adversely affect the operational efficiency of another piece, due to the interdependency of operations. Yet another barrier to operational efficiency is the variation between the physical conditions of different jobsites. When addressing these issues, traditional construction planning schemes have aimed to maximize the production rate of overall operations (reducing time), and to minimize the cost. Adding an environmental perspective to this issue could have a big impact on planning decisions.

This chapter presents a methodology to integrate operational efficiency into the environmental impact assessment of construction operations, and to investigate to what extent the environmental impact of operations could be affected by operational decisions at the project level. The chapter begins with a review of the previous studies that assessed the environmental impact of construction operations and methodologies in order to quantify the construction emissions. The chapter then discusses the methodology for an effective incorporation of the analysis of operational efficiency—which will result from discrete-event simulation models of

construction operations—into the assessment of the environmental impact. The result from the representative case study is used to demonstrate that the presented methodology could bring a significant change to decision-making with regard to the mitigation plans for environmental impacts of construction operations. The result is also used to examine the impact that decisions to reduce environmental impact have on the time and cost performance of a project.

2. PREVIOUS STUDIES

Previous studies that were introduced in Chapter 2 assessed the impact of exhaust emissions—from both on-site operation of construction equipment and on-site/off-site transportation—as one of the major contributors to the life-cycle environmental impact of construction operations. However, these previous efforts tend to ignore additional environmental impact due to possible operational inefficiency of construction processes, since their focus is to reveal the overall environmental impact in a large context, such as 30 ~ 50 years of the entire building/infrastructure life-cycle or the total emission amount in the national or state level. Rather, these efforts assume the average but constant efficiency level, no matter how the operations are executed, or under what conditions. However, when it comes to the controllable amount of environmental impact from construction operations, the impact of the operational efficiency of construction processes would be significant.

Lewis et al. (2011a) and Lewis et al. (2011b) investigated the impact of operational efficiency on the emissions of a piece of equipment. Based on their study of the ratio of idle to non-idle emission rates of construction equipment, they presented a methodology to estimate the percentage of additional pollutants emitted from a piece of construction equipment depending on its various operational efficiencies. Previous studies, however, lacked an empirical approach to the operational efficiency of construction equipment, therefore Lewis et al. used the common

value of job efficiency from general construction estimating practices. This common value of job efficiency defined the actual number of minutes worked during an hour, and accounted for operator breaks and other work interruptions (Caterpillar 2010). For example, general construction estimating practices define about 88% of operational efficiency for most projects, based on the assumption that a worker breaks for 10 minutes every hour. In this concept derived from an estimating practice, operational efficiency is considered to be the result of a workplace policy that defines workers' breaks. Therefore, with this definition of operational efficiency, the variability of the operational efficiency in construction operations cannot be incorporated robustly.

However, as discussed in Chapter 3, the operational efficiency of equipment, which was defined as operation equipment efficiency (OEE), is greatly affected by resource allocation and schedules, job site conditions, and other project characteristics and also controllable with the planning and control actions in the operations.

3. METHODOLOGY

This section presents the methodology for integrating operational efficiency into the assessment of exhaust emissions from construction operations. First, it describes how the equation to quantify construction exhaust emissions can be reformulated with the inclusion of an OEE. Then, it discusses the method to predict OEEs in construction operations and the determination of the emission factors to be used in the re-formulated equation.

3.1. Integration of Operating Equipment Efficiency into the Quantification of Exhaust Emissions

In the previous efforts to assess environmental impact, the quantification of construction exhaust emissions mainly depended on the emission factors of the NONROAD model (EPA 2009c); the OFFROAD model (CARB 2009a) is a substitute for the NONROAD model in California. The NONROAD model, developed by the EPA, is designed to provide state and local pollution control agencies with the ability to easily create and project accurate and reproducible inventories of emissions from non-road equipment, including construction, agricultural, and industrial equipment, as well as locomotives and aircrafts. The model provides emission and load factors (average proportion of rated power used) by type, power level, and age of equipment. The model also provides an estimation of the engine population and annual activity (operation hours) by equipment type and power level (EPA 2010a). The local environmental agencies can thereby easily create emission inventories of the non-road equipment in their regions.

The emissions generated from equipment fleet use (or intended use) in construction operations could then be calculated by combining the reported or estimated activities (operation hours) of the construction equipment fleet with emission and load factors of the model, as shown in the following equation (EPA 2010a):

$$Emissions = \sum_{equipment} A_i \times LF_i \times EF_i \quad (4)$$

where A_i = Activity (operation hours), LF_i = Load Factor (no unit), and EF_i = Emission Factor (grams of air pollutant/hours of activity).

Load factors of the NONROAD model representing the average amount of engine power, including periods of idling and inactivity, are intended to incorporate the OEE of equipment into the estimation steps. Due to limited empirical research, a constant value of load factors is given

to one type of equipment. For example, any excavator is assumed to have 0.56 load factors over the course of its operation period (EPA 2010a). In other words, all excavators are assumed to have the same OEE over the course of their operations. This assumption is valid when assessing the level of emissions from hundreds of excavators across the county or state, but is inadequate when developing a reliable quantification of emissions from several excavators used in a construction project. Gallivan (2010) also drew attention to the uncertainty issue of load factors of the NONROAD model in quantifying emissions from construction off-road equipment.

When dividing the total operating duration of equipment into valuable operating (working) and non-valuable operating time (idling), the equation to calculate the amount of emissions generated from equipment fleet use can be re-formulated with the introduction of OEE, as shown in the following equation:

$$Emissions = \sum_{equipment} A \times EF_{valuable} \times (OEE + (1 - OEE) \times \rho) \quad (5)$$

where A = Activity (hrs); OEE = Operating Equipment Efficiency; $EF_{valuable}$ = Emission Factor for valuable operating time (working modes) (g/hr); and ρ = the generalized ratio of idle to working emission rate of construction equipment (Lewis et al. 2011a; Lewis et al. 2011b), respectively.

Valuable operation of the equipment includes the various actions performed, referred to as activity modes (Lewis et al. 2011b). For example, the operation of an excavator includes various activity modes, such as moving and using buckets. Different activity modes of equipment yield different levels of emission rates, but the difference between emission rates from different activity modes during valuable operation was quite small compared to the difference of emission rates between valuable and non-valuable (idling) operation (Abolhassani

et al. 2008). Therefore, the difference between emission rates from different activity modes during valuable operation can be ignored while assessing pollutant productivity of the overall construction operation.

3.2. Prediction of Operating Equipment Efficiency

Compared to the productivity and cost of overall operations, the OEE of each piece of equipment is not of great interest in common construction estimating practice. Since we do not have extensive historical data on the OEE of equipment for a certain task, predicting OEEs has been attempted mostly using the numerical model (e.g., the queuing theory) or the computer simulation model.

In particular, discrete-event simulation (DES) is very effective for this purpose, by building computer models that represent the following: the overall logic of works required to complete a project, the various resources involved (crews, equipment, management, etc.), and the environment in which the work is happening (e.g., ground conditions and labor pools) (Martinez 2010). A well-developed DES model can therefore provide a robust estimation of the idling rate of each piece of equipment, in accordance with each piece's operation plans and jobsite conditions.

A DES model to predict the OEE of each resource should be somewhat different than one meant to estimate an operation's global variables such as cost, time, and productivity. The task performed by each resource should be broken down to a lower level that differentiates valuable and non-valuable operating activities. For instance, a crane's task of installing material should be divided into three micro-activities: lowering (valuable), holding (non-valuable), and lifting up material (valuable).

3.3. Determination of Emission Factors

As mentioned earlier, the data in the NONROAD and OFFROAD models cannot fully link emissions to equipment's activity modes. To address this issue, North Carolina State University collected data on field fuel use and exhaust emission from construction equipment performing real-world activities, using a portable emission measurement system (Frey et al. 2010). Based on this data, Lewis et al. (2011a) presented the generalized ratio of idle to non-idle fuel use rates and CO₂ exhaust emission rates for each type of construction equipment. This study provides a basis for determining the value of ρ in Equation (5) and thus once the emission rate of non-idle modes, $EF_{valuable}$ in Equation (5), is known, the idle emission rates for each type of construction equipment can be determined. With that said, there are still challenges in determining emission rates of non-idle modes of construction equipment that should represent only the valuable operating of equipment without any idling under real-world conditions. Again, most existing data on exhaust emission factors of construction equipment represent the average emission rate of overall equipment operation (including valuable operating and non-valuable operating), based on the assumption of average OEE of equipment (the average ratio of non-valuable operating time to total operating time).

To address challenges in the existing sources of emission rates, in this chapter, non-idle exhaust emission rates of construction equipment in case studies (which will be described later) are determined based on fuel consumption data from the Caterpillar Performance book (2010). The Caterpillar Performance book provides fuel consumption rate according to equipment type, engine size (model), and application type, and is measured over a period of time without any break- or idle time. In the case of other manufacturers' equipment, a model that has the same

engine size is chosen within the category for corresponding equipment type in the Caterpillar Performance book (2010). CO₂ exhaust emission rates are then determined based on the emission factor of diesel (EPA 2008b); the CO₂ exhaust emission rate is directly proportional to the fuel consumption rate, since around 99% of the carbon content in transportation fuels is oxidized into CO₂.

4. CASE STUDIES

Two case studies are presented here in order to illustrate how planning decisions can affect the pollutant productivity of a real-world operation by changing the OEE of each resource.

4.1. Case Study 1

The first case study is an earthmoving operation, performed in an open field. The earthmoving tasks in this project, as a whole, were estimated to generate 652 tons of carbon emissions. This estimation was completed using the NONROAD model. One of those tasks was chosen to predict the carbon emissions with the use of the presented method, and to identify emission reductions from alternative scenarios in the planning phase. The task investigated here was the excavation (around 60,095 cubic yards of topsoil), hauling (1.6km), and the placement (into a stockpile). The dumping area was located within the jobsite, so traffic interruption was not an issue. The base scenario that the contractor planned was to deploy two excavators (Komatsu EX 850) and 11 dump trucks (CAT 740). The contractor determined the number of dump trucks based on the ratio of cycle time of a scraper to cycle time of a pusher, which is the rule of thumb in general estimating practice (Caterpillar 2010).

A discrete-event simulation (DES) model was developed for the base scenario, using Symphony.NET, which is a visual discrete event simulation package specialized for construction

systems and developed at the Hole School of Construction Engineering and Management, University of Alberta, Canada (AbouRizk and Mohamed 2000). Excavators and trucks were represented as resources in the model, and each equipment activity (loading, dumping, exchanging trucks, hauling, and returning) was represented as a task, as shown in Figure 5.1.

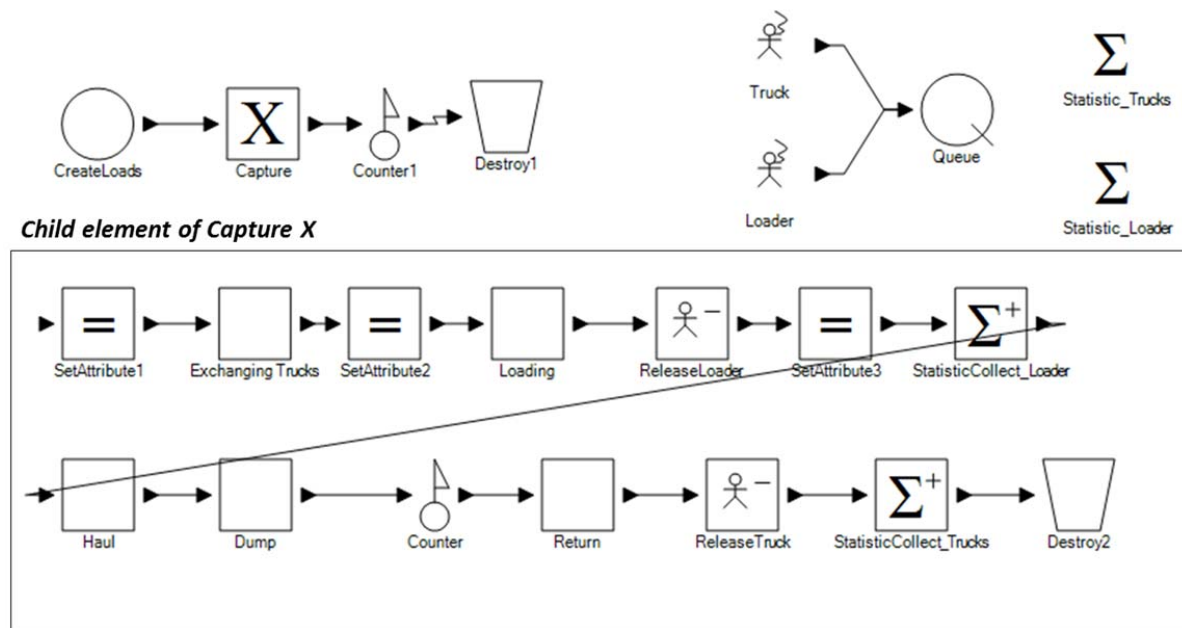


Figure 5.1. Symphony.NET model of Case Study 1

Data on the duration of each activity of equipment was collected from the manual observation on a day of the previous task that involved the same set of construction equipment fleet. The distribution of each activity was determined using the statistical tool, based on the data set except outliers, and its goodness of fit was tested through the Kolmogorov-Smirnov (K-S) test. The distributions of hauling and returning activities of trucks were updated based on the difference of the distance between the observed task and the given task (Table 5.1). For example, the distribution of excavators' loading activity was determined as a continuous uniform distribution on the interval between 1.5 and 3 minutes, based on 20 observations. The distribution was accepted at the significance level of 0.05 through the K-S test.

Table 5.1. Estimated duration of equipment operation in Case Study 1

Equipment	Operation	Distribution ¹
Excavator	Loading	Uniform (1.5, 3)
Trucks	Exchanging in the queue	Uniform (0.9, 1.1)
	Hauling	Triangular (3, 7.5)
	Dumping	Uniform (0.75, 2.25)
	Returning	Triangular (1.32, 3.08)
¹ estimated based on contractors' baseline plans and observations of previous earthmoving tasks in the project.		

Based on observations from previous tasks, excavators are assumed to be idling (non-valuable operating) while trucks exchange in order to be loaded, or while excavators wait for trucks (no truck in the queue). Trucks are assumed to be idling (non-valuable operating) when they are in the waiting queue for excavators, or when in the loading task. The emission rate for non-idle modes of equipment was calculated based on the fuel consumption data from the Caterpillar Performance book, and the emission rate of idling modes was determined using the ratio of idle to non-idle fuel use (ρ in Equation (5)), which Lewis et al. (2011a; 2011b) provided. The detailed data on equipment specification and emission rate of each activity mode is summarized in Table 5.2.

Table 5.2. Specifications of equipment of Case Study 1

Equipment type	Excavator	Off-highway Truck
Model	Komatsu EX750	Caterpillar 740
Horsepower	446	469
Average Fuel consumption (gal/hr) ¹	12.8	7.35
Emission rate (kg CO ₂ /hr) ²	124.8	74.6
The ratio of idle emission rate to non-idle emission rate ³	0.2	0.2
Owning and operating cost (\$/hr) ⁴	389	248
¹ estimated based on Caterpillar (2011); ² calculated with diesel emission factor (EPA 2011); ³ Lewis et al. (2011a); ⁴ RS Means (2011), including labor cost and O&P cost		

In total, 30 runs of the simulation model were sampled for analysis. The simulation

results for the base scenario indicated that, over the total duration of the task, excavators had an OEE of 69% with a standard deviation of 0.08%, and trucks had an OEE of 54% with a standard deviation (σ) of 0.17%. As a result, 5.3 metric tons of carbon emissions ($\sigma=0.025$) were generated from non-valuable operation of equipment, while the total amount of carbon emissions is estimated to be 41.6 metric tons ($\sigma=0.073$). The OEE of excavators, at 69%, is quite close to a minimum, considering the cycle time of exchanging trucks and the loading task. However, that trucks' OEE was at 54% suggests that unnecessary idling occurred due to lengthy waiting lines for excavators. Such a low OEE of trucks is mainly due to the general estimation practice's tendency to pursue the highest production rate by ensuring that there are enough trucks for each excavator.

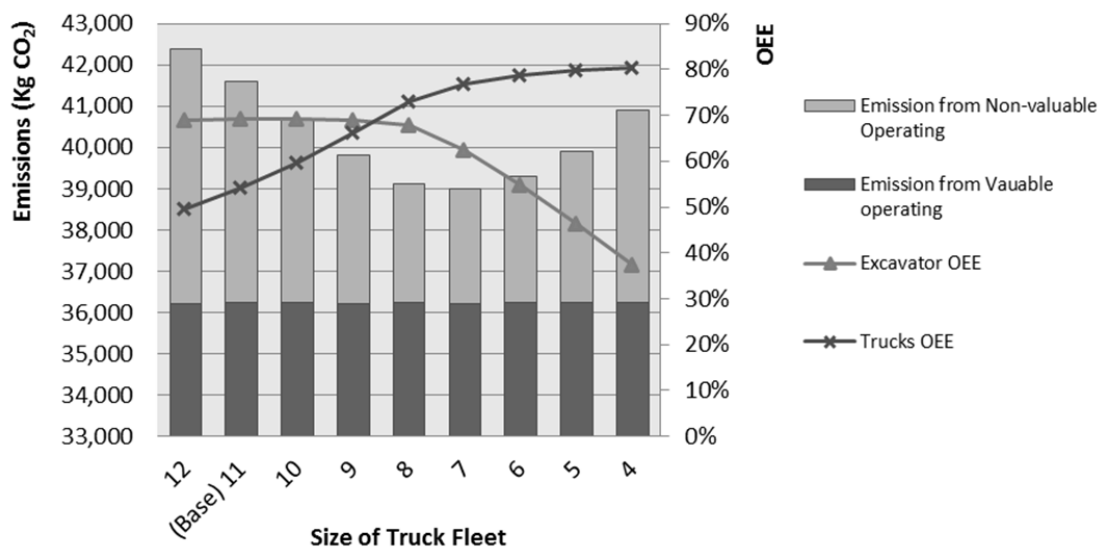


Figure 5.2. CO₂ emissions and the OEEs of different scenarios of Case Study 1

In order to identify the impact of different operational settings, we changed the fleet size of trucks and analyzed the change's impact on the OEEs of equipment and total emissions. Figure 5.2 summarizes the results from different truck fleet sizes. The amount of emissions

during the valuable operating period of equipment is rather constant regardless of differing fleet configurations, and only depends on the total amount of work to be done. For example, the number of haulings is determined only by the amount of excavated soil and the capacity of a truck, rather than the number of trucks or excavators. On the other hand, the amount of emissions during the non-valuable operation of equipment is greatly affected by the fleet configuration. As a truck fleet becomes smaller, the OEE of its trucks increases. Beyond a specific size of truck fleet (in this case, nine trucks), the OEE of excavators begins to decrease as trucks become a constraint resource of the overall operation. Therefore, a tradeoff occurs between the OEE of excavators and trucks. The results indicated that the pollutant productivity in the overall operation can be greatly improved by decreasing the OEE of excavators and increasing the OEE of trucks. This is because, in this operation, truck fleets are a bigger emission source than excavator fleets. As expected, at some point a truck fleet is too small, and so weakens the production rate and generates more emissions. 48% of emissions from non-valuable equipment operating can be reduced by adjusting the number of trucks from the baseline scenario to seven, and this would result in a 7% improvement in the overall carbon productivity (i.e., cubic yards of dirt excavated per metric tonnes of carbon emissions emitted (yd^3/tCO_2) in this case). This decision would cause the deterioration of schedule performance (yd^3/hr), but would ensure better cost performance ($\text{yd}^3/\text{thousand dollar}$), as shown in Figure 5.3.

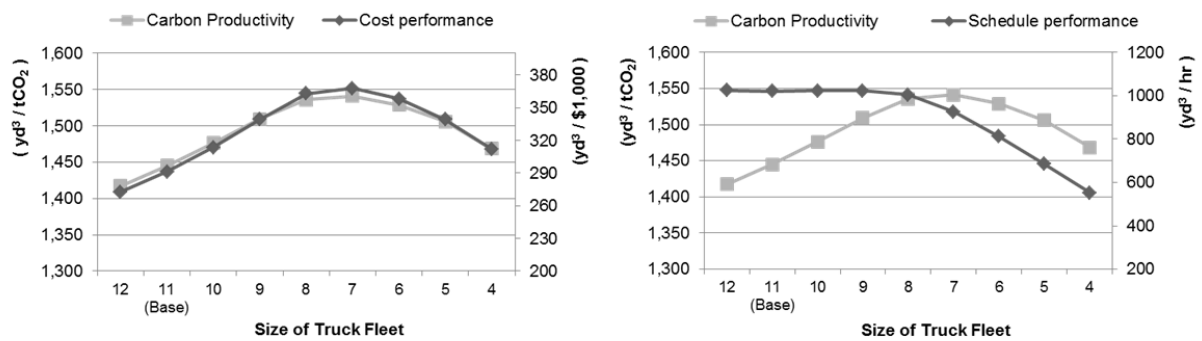


Figure 5.3. (Left) Carbon Productivity and Cost performance (Right) Carbon Productivity and Schedule performance of different scenarios of Case Study 1

4.2. Case Study 2

The second case study is an underpass project in a dense urban area. The task investigated in the project is the excavation of around 22,100 cubic yards of soil and the hauling of it to the dumping area located about 25 miles away. Two small excavators on the underground level excavated dirt and loaded it into a trailer. A crawler crane on the ground level lowered and lifted a trailer between the underground level and the ground level. The crane was also utilized for material handling while it did not engage in the excavation work. Multiple trucks were deployed as hauling units to a remote dumping site; the number of trucks used was decided on a daily basis, and was either three or four.

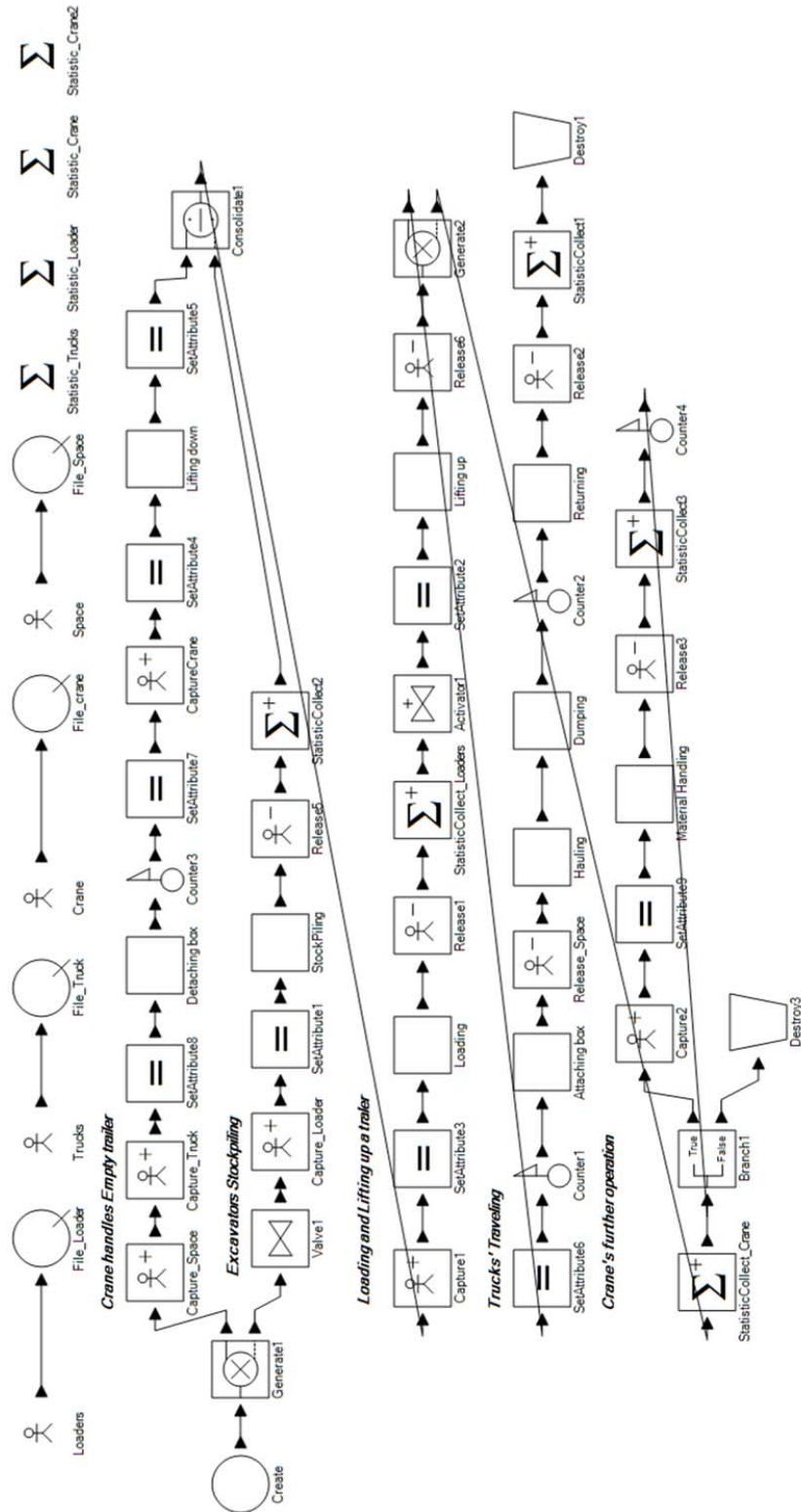


Figure 5.4. Symphony.NET model of Case Study 2

The OEE of the excavators was observed to be very low, around 30%, since (1) the inter-arrival time between hauling trucks was quite long due to a remote dumping site; (2) the travels of hauling trucks were often delayed due to traffic jams; and (3) detaching/attaching a trailer from a truck and lifting/lowering it created a significant waiting period for excavators within one production cycle. The crane had some amount of idling when it had to wait for the lifted trailer to be filled. Trucks, though, didn't have much idling, since truck drivers shut off their engines during their waiting time. The emissions from trucks, therefore, are not accounted for in the assessment of the pollutant productivity of this case study. Based on the observations, a DES model was developed to examine both the OEE of equipment (particularly the excavators and crane) and the carbon productivity of this task, using Symphony.NET. The developed DES model is presented in Figure 5.4. The crane's operation is modeled to engage in the excavation work as the top priority and to be employed for material handling as the second priority. Accounting for the OEE and cost of the crane in this case study was thus based on only the time in which the crane engaged in the investigated task. The estimated distributions of equipment activities are summarized in Table 5.3. Data on the duration of each activity of the excavators and the crane was collected from the manual observation of two days of this on-going task. Data on the duration of each activity of the trucks was collected from truck delivery tickets that had been gathered for two weeks of this on-going task; truck delivery tickets specified each time that trucks depart or arrive at the jobsite and the dump site. For example, the distribution of the truck hauling activity to the original dumping site was determined as a normal distribution, based on 42 data points. The distribution was accepted at the significance level of 0.05. The minimum value of the distribution was set based on the allowable maximum speed of trucks.

Table 5.3. Estimated duration of equipment operation in Case Study 2

Equipment	Operation	Distribution
Crane	Lowering an empty trailer	Uniform (3,5) ¹
	Lifting a loaded trailer	Uniform (3,5) ¹
Excavator	Stockpiling	Uniform (5, 8) with 2 excavators ¹ Uniform (10,16) with 1 excavator ²
	Loading	Uniform (15, 20) with 2 excavators ¹ Uniform (30,40) with 1 excavator ²
Truck	Detaching a trailer	Uniform (8,10) ¹
	Attaching a trailer	Uniform (10,15) ¹
	Hauling	Normal (124.83, 23.01) with minimum value of 60: Original dumping site ³ Cauchy (67.78, 8.67) with minimum value of 45: New dumping site ³
	Returning	Gamma (4.2, 20.7): Original dumping site ³ Gamma (8.13, 9.30): New dumping site ³
	Dumping	Uniform (9,11) ³
¹ based on manual observations on on-going operations; ² estimated based on the number of excavators; ³ based on the truck delivery tickets collected over the course of two weeks for each dumping site.		

Using a DES model, with three trucks, the OEEs of the excavators and the crane is estimated to be 25% ($\sigma=0.15\%$) and 31% ($\sigma=0.10\%$), respectively. Around 14.3 tons of carbon emissions ($\sigma=0.084$) were generated by non-valuable equipment operation, while around 40.8 tons of carbon emissions ($\sigma=0.14$) were generated in total from the excavators and the crane. This level of emissions from non-valuable equipment operation is significant, since almost 35% of total carbon emissions from the excavators and crane were generated from non-valuable operation. Further, such an ample commitment to non-valuable activity of a resource may lead to low schedule and cost performances of overall operations.

The alternative to enhancing the OEE of excavators is increasing the number of trucks, such that the inter-arrival time between them is shorter. The OEE of the excavators improves as the size of the truck fleet increases up to six, and stabilizes at 43% beyond six trucks. Therefore,

compared to the baseline scenario, the amount of non-valuable emissions reduces by 48%, and the overall carbon productivity enhances by 15%. The schedule performance also enhances by 71% while the cost performance stays at a similar level as shown in Figure 5.5. Although implementing this alternative could bring such improvement of project performances, the implementation would be hindered by a space constraint of the jobsite. The simulation results indicated that the time in which more than two trucks stand by on the jobsite increases from 3% to 56% of the total duration of the task. However, the jobsite has a space for only one truck, and therefore, the implementation of this alternative requires additional space for a truck waiting zone outside the jobsite.

Another alternative is the reduction of the number of employed excavators. Apparently, the smaller the excavator fleet size, the larger the cycle time for tasks of the excavators (e.g. loading, stockpiling), but the higher the OEE. The simulation results indicated that this alternative would improve the carbon productivity by 4%, and would also mean an 18% increase in the cost performance (Figure 5.5). However, the implementation of this alternative deteriorates the schedule performance, and more importantly, it decreases the OEE of the crane because the waiting time of the crane (for an empty trailer to be filled by the excavator) increases. The simulation results indicated that the crane's OEE decreased from 31% to 19% when the smaller excavator fleet was employed. This causes the delay of other activities with which the crane is involved, considering that the crane is usually the most critical resource in an urban project.

The last alternative is to change the dumping site to be located closer to the jobsite. This would shorten travel time for trucks and increase the OEEs of excavators by ensuring a shorter inter-arrival time between trucks. In fact, this alternative was implemented over the course of the

project in order to expedite the schedule, rather than to reduce emissions; the new dumping site was located around 7.5 miles from the jobsite. The distribution for the truck traveling time to the new dumping site was developed based on a week's collection of truck delivery tickets. The simulation results indicate that this would result in a 5% enhancement of the carbon productivity, along with 30% and 19% improvements in cost and schedule performance (Figure 5.5). Note, though, that the cost performance of this alternative did not account for the new dumping site potentially raising disposal fees, such that this alternative's true cost performance may not be that greatly enhanced.

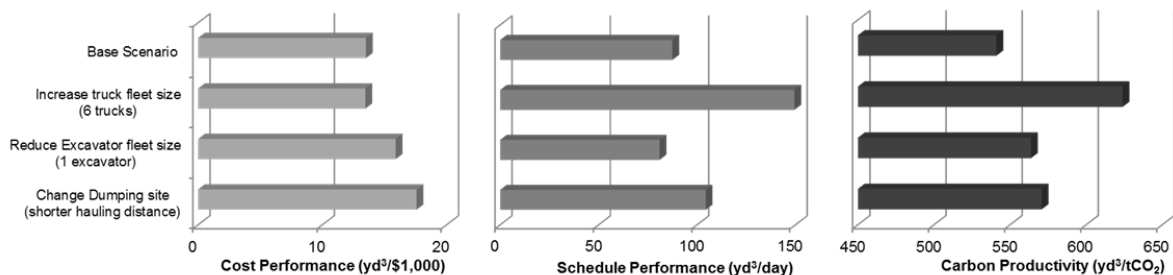


Figure 5.5. Cost, Schedule, and Carbon Productivity of different alternatives – Case Study 2

5. DISCUSSION

Reducing air pollutant emissions from construction operations could be accomplished by enhancing the fuel efficiency of equipment (e.g. replacing older equipment, retrofitting existing equipment) and reducing the emission intensity of fuel used (e.g. using biodiesel and ultra-low-sulfur diesel), in addition to controlling the OEE of equipment. However, the variables of equipment fuel efficiency and fuel emission intensity are nearly fixed once a project has started, and their improvement requires significant up-front costs. In this context, controlling the OEE of equipment is the only strategy that can be approached from the current construction management framework, and is the most cost-effective strategy among all possible strategies including enhancing equipment fuel efficiency and fuel emission intensity. The findings from the case

studies suggest that the amount of emissions from valuable equipment operation is constant no matter how operational settings and plans change, as long as the fuel efficiency and emission intensity do not change. Therefore, the overall pollutant productivity relies heavily on the amount of emissions from non-valuable equipment operation which is determined by the OEEs of each piece of equipment.

In a typical construction operation, in which many pieces of equipment are employed and the operation of each piece depends on the operation of the other pieces, a trade-off usually occurs between the OEEs of the linked equipment. Current construction planning practices tend to resolve such a trade-off in a way that maximizes schedule or cost performance. In reconciling such trade-offs, adding an environmental perspective would provide a chance to improve the project's "integrated-value," which includes schedule, cost, and environmental impact. For example, the baseline plan of Case Study 1 focused on maximizing the OEE of excavators, which starts a production cycle, for a better schedule performance. On the other hand, for a better pollutant productivity, the OEE of trucks is more heavily weighted since the truck fleet is a larger emission source than the excavator fleet. Since the alternative to improve the pollutant productivity also has a better cost performance of Case Study 1 as shown in Figure 5.3, this alternative may provide a better integrated-value of the project and a chance for the contractor to select this alternative increases as the environmental perspective is included in the process of resolving the trade-off between the OEEs of the linked equipment.

The trade-off between the OEEs of the linked equipment is not a new problem and has been studied quite rigorously from the perspective of improving the productivity of operations. In addition, it is somewhat evident that the operational inefficiency of the process will cause additional energy consumption and air pollutants. However, existing environmental impact

assessment models of construction operations do not have adequate capabilities to assess additional environmental impact caused by such operational inefficiency of the process, since their assessment schemes focus on revealing the amount of emissions from valuable operating mainly based on the amount of total work to be done. Therefore, even though construction stakeholders improve operational efficiency and thereby presumably reduce the environmental impact of construction operations, there exist few ways to assess such reduction of the environmental impact in the predictive assessment stage. In this context, integrating the advanced process model, which can predict the change of the operational inefficiency by management actions, into the environmental impact assessment model of construction operations contributes to address this matter, and thereby construction managers can identify the degree of the effect of their change in operational settings on the environmental impact.

Even though case studies in this chapter focused on the impact on carbon emissions, controlling operational efficiency in construction operations significantly reduces other diesel exhaust emissions, such as NO_x, HC, CO, and PM. Mitigation efforts for some air pollutants, such as HC and CO, would benefit from controlling operational efficiency much more greatly, because the ratio of idle emission rate to non-idle emission rate for those air pollutants is higher than that of carbon emissions (Lewis et al. 2011b). In particular, in urban projects like Case Study 2, diesel exhaust emissions have drawn much attention from local public agencies and communities—and more than carbon emissions—since they can directly affect the air quality issue of an urban neighborhood. As shown in Case Study 2, urban projects usually have low operational efficiency and thereby cause a significant amount of additional diesel exhaust emissions. Therefore, the consideration of environmental aspects in the planning of urban projects would provide great opportunities to comply with the regulatory efforts to improve

urban air quality.

A number of states have adopted anti-idling laws that limit the idling of diesel vehicles and equipment to 3-10 minutes (EPA 2006); these laws mainly target on-load vehicles, and some that apply to off-load diesel vehicles even give an exemption to equipment engaged in construction work. Most anti-idling initiatives focus on changing the behavior of operators through education. Behavior modification may prove challenging but is generally considered successful for on-road heavy-duty vehicles, since the greatest reduction of idling comes from reducing the driver's need to idle in order to maintain cabin comfort while sleeping (ICF 2007). However, the effect of operator training could be limited in construction operations compared to on-road heavy-duty vehicles. First, the duration of each idling occurrence in construction operations is often too short to require turning off engines, as the old diesel engines that still occupy most construction equipment require warm-up and cool-down periods. Second, the poor environmental conditions of a jobsite (e.g. high temperature, dust generation) cause operators to idle in order to maintain cabin comfort. In addition, equipment operators are eager to keep themselves busy, rather than wander around their equipment during working hours (Hagerty 2011). In this context, anti-idling initiatives for construction equipment would be better if approached from the management of work-flow within a project, by focusing on better resource allotment and scheduling.

6. CONCLUSIONS

This chapter presents a method for incorporating the analysis of the OEEs of each resource into the assessment of the environmental impact. The results from the case studies have shown that changing operational settings could impact the pollutant productivity by affecting the OEEs of each resource, and would significantly impact decision-making in the planning phase. The results

have also indicated that better pollutant productivity does not always mean sacrificing both cost and schedule performance. Rather, the alternative that has a better pollutant productivity is often found to enhance either cost or schedule performance. Therefore, the consideration of environmental aspects in planning helps construction managers identify an option that will increase the project's "integrated-value," which includes schedule, cost, and environmental impact.

CHAPTER 6

OUTCOME ASSESSMENT MODEL OF ENVIRONMENTAL PERFORMANCE

1. INTRODUCTION

Monitoring the operational efficiency of equipment is vital for managing the environmental performance of construction operations, and for locating room for improvement. However, these monitoring efforts are still very primitive, due to the lack of a practical monitoring method. Several emerging technologies exist that allow accurate monitoring of equipment use, but they are costly to implement, or have compatibility issues with various types of construction equipment. Furthermore, most of them are intrusive measures that require a connection to legacy engine systems, so subcontractors and equipment owners are reluctant to cooperate with their introduction.

The application of low-cost accelerometers has the potential to address the challenges of existing technologies by providing a low-cost and nonintrusive monitoring system of the equipment operation. To this end, this chapter presents a system to measure the operational efficiency of construction equipment using accelerometers, and evaluates its feasibility in a real-world application. The chapter begins with a review of the existing enabling technologies for monitoring environmental performance and operational efficiency. The remaining sections of the chapter describe the experiment and the case studies that were conducted to evaluate the approach used in this chapter.

2. REVIEW OF EXISTING WORK

2.1. Enabling Technologies for Environmental Monitoring

In current practices of construction operations, the only available data to enable the monitoring of environmental performance is the daily report on the use of equipment, which tracks the amount of equipment deployed on a jobsite. This data is used to quantify the environmental impact of equipment in most LCA research on construction processes (Bilec et al. 2006; Cass and Mukherjee 2011). However, these reports contain only information on whether equipment or not is employed, rather than how efficiently it is used. This lack of disaggregated data also hinders the accurate monitoring of environmental performance.

Several emerging technologies exist that allow a more accurate monitoring of the environmental performance through: (1) the direct measurement of exhaust emissions from equipment; and (2) the indirect measurement of emissions via the tracking of fuel consumption or operational efficiency (Ahn et al. 2011). Direct measurement in construction projects is required to measure emissions from the tailpipes of all pieces of equipment. Portable Emission Measurement Systems (PEMS), which are designed to test or assess mobile source emissions for internal-combustion engine vehicles under real-world conditions, provide very accurate data on the amount of exhaust emissions. PEMS are, however, too costly to be employed for the simultaneous monitoring of a number of energy/emission sources in a project. On the other hand, a number of commercially available gas sensors are currently used by the automotive industry. However, most of them are not resistant to the high temperature of diesel vehicle tailpipes, and equipment vibrations and dust further impede the use of such gas sensors in construction operations.

As a means of indirect measurement, construction equipment has on-board diagnostics

(OBD) systems (e.g., OBD-II, EOBD, JOBD, and CAN bus), which allow for the electronic communication of operational status (e.g. RPM, fuel consumption rate, axle speed, coolant temperature, and engine load). This data can be accessed via on-board diagnostic software (in recently manufactured models) or off-board diagnostic tools (Sharif and Lee 2009). However, there is no standardized OBD system protocol for construction equipment between different manufacturers. Moreover, old equipment, which is the majority of equipment in use, does not have OBD supports, and even a piece of equipment with OBD supports requires extensive modification or the installation of additional devices.

Pursuing greater accuracy of environmental data may not be worthwhile unless that greater accuracy provides opportunities to improve environmental performance. For example, knowing an accurate total amount of air pollutants emitted may not be meaningful unless it helps construction managers identify action plans to reduce air pollutants. With that said, tracking operational efficiency (specifically, operating equipment efficiency) is a cost-effective means of providing key information for managing the environmental performance during construction, since it tells construction managers which piece of equipment is operated under a loosely managed plan.

2.2. Vibration Signal Processing for Automotive Application

The vibration signal analysis of vehicles has been widely conducted with the goal of controlling a vehicle and improving passenger comfort (Liu and Huston 2011). The use of internal combustion (IC) engines in vehicles naturally generates high levels of vibration energy while running, which causes undesirable effects via acoustical disturbances, and may eventually lead to mechanical failures because of fatigue (Antoni et al. 2002). However, a certain amount of

vibrational energy is unavoidable, and therefore can be used to monitor engine conditions (e.g. malfunction) (Geng et al. 2003; Antoni et al. 2002). The basic underlying idea of such applications is that every moving component or physical process involved in the operation of an engine produces its own unique vibration signal, which is referred to as the vibration signature (Antoni et al. 2002). Vibration signatures are believed to exhibit the same features when created by the same engine operating under the same conditions.

This idea also motivates the measurement and analysis of vibration for monitoring the OEE of construction equipment. While the condition monitoring of IC engines using vibration signal analysis still remains challenging due to the complexity of vibration signals (Antoni et al. 2002), detecting activity modes of equipment (e.g. engine off, idle, working) is a simpler application. This is because different activity modes exhibit a clear difference in vibration signatures, while condition monitoring of IC engines (e.g. engine fault) relies on a more subtle difference.

3. RESEARCH OBJECTIVE AND METHODOLOGY

The objective of this research is to test the hypothesis that signals captured by MEMS accelerometers that are installed to construction equipment can be used to analyze the operating equipment efficiency of that equipment, which indicates the ratio of the valuable operating time (non-idling) to the total operating time of the equipment. More specifically, the research aims to demonstrate the feasibility of the classification of the operation of construction equipment into three activity modes—such as working, idling, and engine-off—based on signals captured by a sensor. The underlying idea of the hypothesis is twofold: first, any non-stationary operating of construction equipment (e.g. driving) will create a notable level of acceleration that can be detected by a sensor; second, any stationary operating of construction equipment (e.g. controlling

excavators' boom) will generate distinguishable patterns of vibration signals compared to the idling and engine-off modes. The former idea has already been demonstrated by the application of accelerometers to detect passenger vehicle motion (MacDonald 1990), but the latter idea needs to be demonstrated due to limited previous studies on the vibration of construction vehicles.

In this context, the initial experiment is designed to measure and analyze vibration signals captured during the stationary operating of construction equipment. The experimental result is analyzed in the time domain, and the effect of equipment activity modes on vibration signals is tested using analysis of variance (ANOVA). Next, case studies are conducted in order to evaluate the feasibility of the proposed approach in the real-world applications that involves the stationary and non-stationary operating of equipment. The effect of equipment activity modes on vibration signals is also statistically analyzed, and the feasibility of detecting operational efficiency using signals from an accelerometer is evaluated based on an overall error rate.

Acceleration signals from construction vehicles under the study were measured using a sensor (accelerometer) mounted inside the cabin of vehicles, and the operation of construction vehicles during the study was videotaped. The sensor used was the one embedded in a smartphone, which can sense acceleration in the x-, y-, and z-directions. The sensitivity of the sensor was 16.2 mg (milli-g)/digit, and its measurement range was $\pm 2g$. The signals acquired by an accelerometer are sampled at a rate of 100 Hz. The mounting location of a sensor varies by vehicles, but it is generally mounted on a rigid block around the control system within the cabin of vehicles. Video recordings of vehicle operations are used to label actual operational modes of second-by-second vehicle operation; a vehicle is determined to be idling if it does not show any physical movement for more than three seconds, regardless of its engine status.

4. EXPERIMENTAL ANALYSIS

The experiment is designed and conducted to analyze signals from a stationary operating of construction equipment. The goal of the experiment design is to provide conditions that would generate the greatest difficulty in detecting the difference of vibration signals among stationary operating, idling, and engine-off modes. For this purpose, a recently manufactured excavator is chosen, as newer vehicle models usually generate a lower level of vibration due to the advance of vibration control technologies. Then, the operator is asked to idle for several seconds after turning on the excavator, then very slowly swing up and down the boom of the excavator without moving the body during the experiment.

The signals are captured for around 87 seconds. Figure 6.1 shows vibration signals in three axes after detrending; detrending is a preprocessing step to subtract the mean value from time-series signal data. The signal patterns in the three axes are found to be identical in terms of increasing and decreasing trends, but the levels of amplitudes in the three axes are different. The operational mode of each time segment was determined based on a video recording. The excavator was in engine-off mode from 0 ~ 20 sec and 82 ~ 82 sec, in idling mode from 21 ~ 33 sec and 71~ 81 sec, and in stationary working mode from 34 ~ 70 sec. Different activity modes are observed to have different levels of amplitude variability. When the engine is turned on and off, spikes in the signal are observed. The spikes at around 85 seconds are assumed to be caused by external noise (most likely from the operator unintentionally hitting the accelerometer).

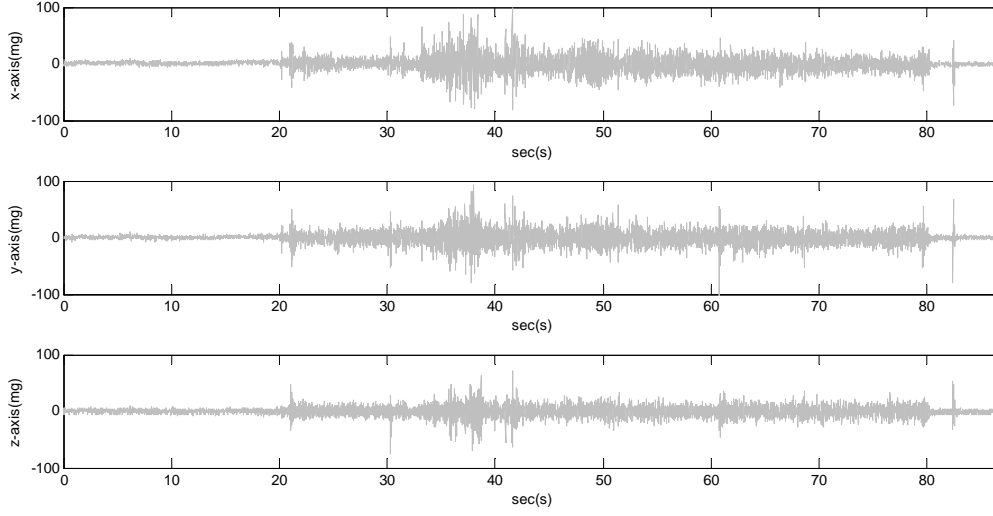


Figure 6.1. Acceleration time histories in the Experiment

Different levels of amplitude variability by activity modes inspire a comparison of the root mean square (RMS) value of signals between different activity modes. The RMS value of a vibration signal is a time analysis feature that represents the power content in the vibration signature (Lebold et al. 2000). Although RMS is not an inherent signal processing technique, it is a widely used feature in signal processing and classification due to its simplicity. The RMS value for the x-axis is calculated as

$$x_{RMSk} = \sqrt{\frac{1}{M} \sum_{i=1}^M (x_{(k-1)M+i})^2} \quad k = 1, 2, \dots, \left\lfloor \frac{N}{M} \right\rfloor.$$

where N is the total number of points in a time series and M is the number of points in time series interval used in analysis. The RMS values for the y- and z-axis data can be combined to form the RMS acceleration vector magnitude, as follows:

$$accel_{RMSk} = \sqrt{x_{RMSk}^2 + y_{RMSk}^2 + z_{RMSk}^2}.$$

Figure 6.2 shows the RMS values in regular time intervals (1 second). The RMS values are classified into three groups based on the activity mode of their time frame. In this procedure, 2 time frames that include signal spikes due to the engine turning on and off are discarded. Figure 6.3 shows a box plot of the distribution of three groups; the data points are drawn as outliers if they are larger than the 75th percentile or smaller than the 25th percentile by 1.5 times of the interquartile range. The RMS value of the engine-off group indicates the level of noise, and it is observed that any operation of the equipment including idling generates a distinguishable level of the vibration amplitude compared to the noise. Also, idling and stationary operating groups have different ranges of the value, although the lower boundary of the stationary operating group (between the smallest value and the 25th percentile) overlaps with the idling group; it is thought that the data points in the overlapped range represent the time frames in transient mode between stationary operating and idle modes.

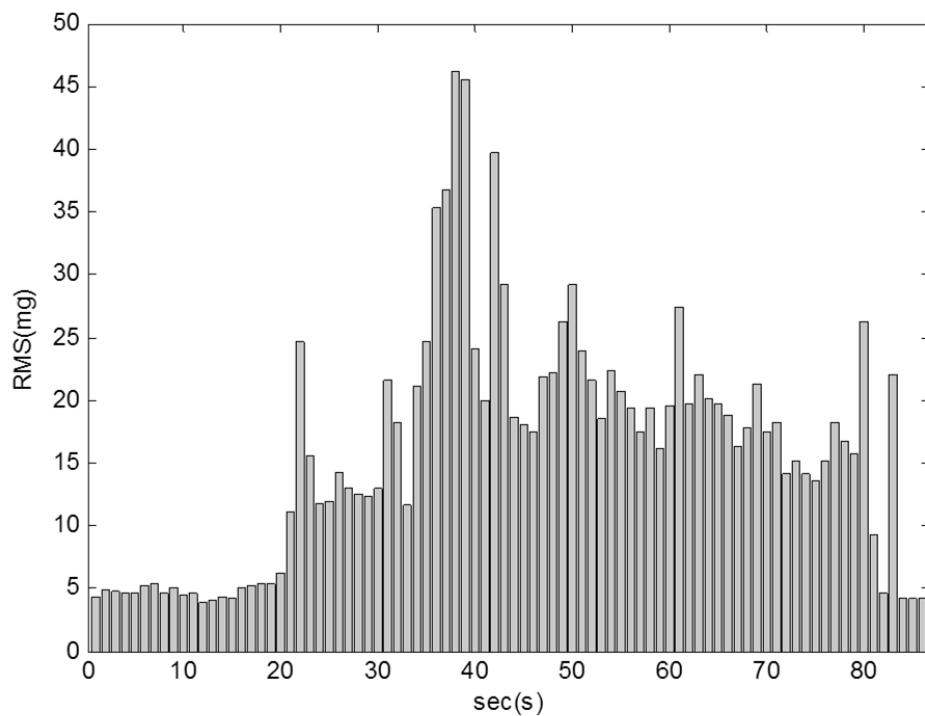


Figure 6.2. RMS value of a time series in the Experiment

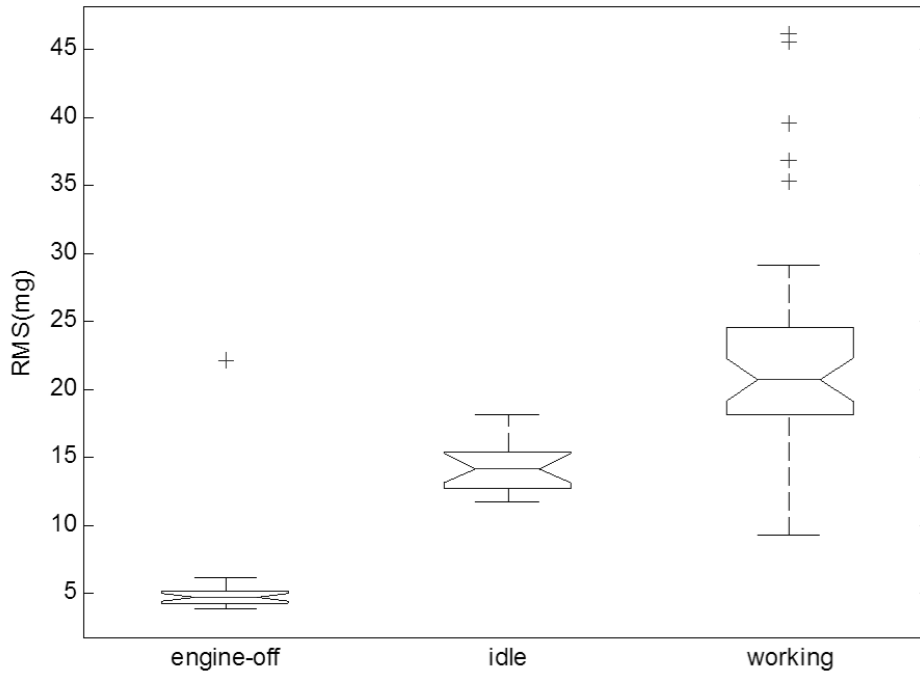


Figure 6.3. Box-plot of RMS values of different activity modes in the Experiment

The data shown in Figure 6.3 were further employed for ANOVA to confirm that each group has statistically significantly different distribution of RMS values from others. The results of ANOVA are listed in Table 6.1. It is clear from Table 6.1 that the RMS value of the signals, which represents the vibration amplitude, is influenced by the activity mode of the excavator. This result demonstrates that engine-off, idling, and stationary operating of an excavator generates distinguishable patterns of vibration signals, and that the RMS value of vibration signals is a good signal feature in classifying the time frames of construction vehicle operating into different activity modes. One challenging issue is the uncertainty of the boundary estimate, which arises due to the transient mode of equipment between working and idle modes.

Table 6.1. Analysis of variation in the Experiment

Source	Sum Square	Degree of freedom	Mean square	F ratio	P value
Activity mode	4891.17	2	2445.59	66.97	0
Error	3067.55	84	36.52		
Total	7958.73	86			

5. CASE STUDIES

This section describes the case studies conducted in order to evaluate the feasibility of monitoring the operational efficiency of construction vehicles in real-world operational settings using the signals captured by an accelerometer. The main focus is how reliably the idling can be detected in a real-world operation of construction vehicles that involves the various types of the stationary and non-stationary operation of equipment. Three different excavators that perform various real-world work tasks are chosen for the case studies.

The RMS value is selected as a feature for classifying the signals, based on the result of the previous experimental analysis. Each time frame in case studies is classified into working and idle modes, based on the RMS value. The classification errors are then identified based on the comparison with visual observations. There are two types of errors, *working errors* and *idling errors*. The former error indicates that the time frames known to contain working are not classified as working modes. The latter error indicates that the time frames known to contain idling are not classified as idling modes. An overall classification error rate, a working error rate, and an idling error rate are then calculated as:

$$Err = \frac{N_{Err_w} + N_{Err_i}}{N_w + N_i}, \quad Err_w = \frac{N_{Err_w}}{N_w}, \quad Err_i = \frac{N_{Err_i}}{N_i}$$

where Err , Err_w , and Err_i are an overall classification error rate, a working error rate, and an idling error rate, respectively. N_w and N_i are the total number of time frames that are known as working and idling. N_{Errw} and N_{Erri} are the number of *working error* and *idling error* time frames.

The possible minimum value of an overall classification error rate in each case study is assessed as a mean of evaluating the feasibility of the proposed approach. A minimum error rate is determined as follows: each RMS value existing in a range between the 75th percentile value of the idling RMS distribution and the 25th percentile value of the working RMS distribution in each case study is chosen as a threshold RMS value that works as a classifier to distinguish working and idling time frames; overall classification error rates using each threshold value are calculated, and a minimum value among them is reported.

5.1. Case study 1

The first case study is conducted for a medium-sized crawler excavator that was analyzed in the previous experiment. The excavator is performing real-world utility work that involves digging a trench and placing wooden trench boxes. The observation ran for around 30 minutes, during which time the excavator was kept running and was not turned off. While digging a trench required quite tumultuous actions of the excavator, placing wooden trench boxes involved relatively modest actions.

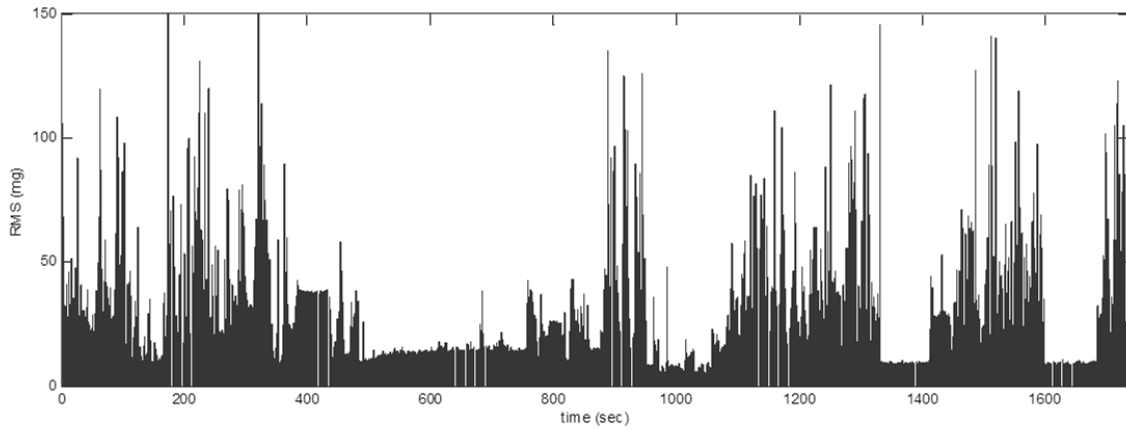


Figure 6.4. RMS time series of Case Study 1

Figure 6.4 shows the time series data of the RMS value during the entire observation, and Figure 6.5 shows a box plot of the RMS distribution of working and idle time frames. The clear difference of the RMS distribution between working and idle time frames is found; the statistical analysis using t-test ($P < 0.01$) confirms that the activity mode of the excavator affected the RMS values of time frames. The RMS threshold value that generates a minimum error rate is determined to be 11.5 mg, based on the previously described algorithm. Figure 6.6 shows the result of the classification using this RMS threshold value. The time frames that have lower RMS values than the threshold are marked as dark gray bars and the time frames that are truly in an idling mode are marked with dotted-line boxes. The overall error rate is assessed as 8%, while the *working error* rate is assessed as 3%, and the *idling error* rate is assessed as 25%. The result is found to have a relatively high error rate in the classification of short idling periods (i.e., periods shorter than 10 seconds), while it is highly accurate in the classification of long idling periods (i.e., periods longer than 10 seconds). For example, the long idling periods occurring between 490 and 510 seconds, 950 and 1060 seconds, 1325 and 1415 seconds, and 1600 and 1682 seconds have been very accurately classified, but it fails to detect the short idling periods

occurring around 560 seconds and 800 seconds.

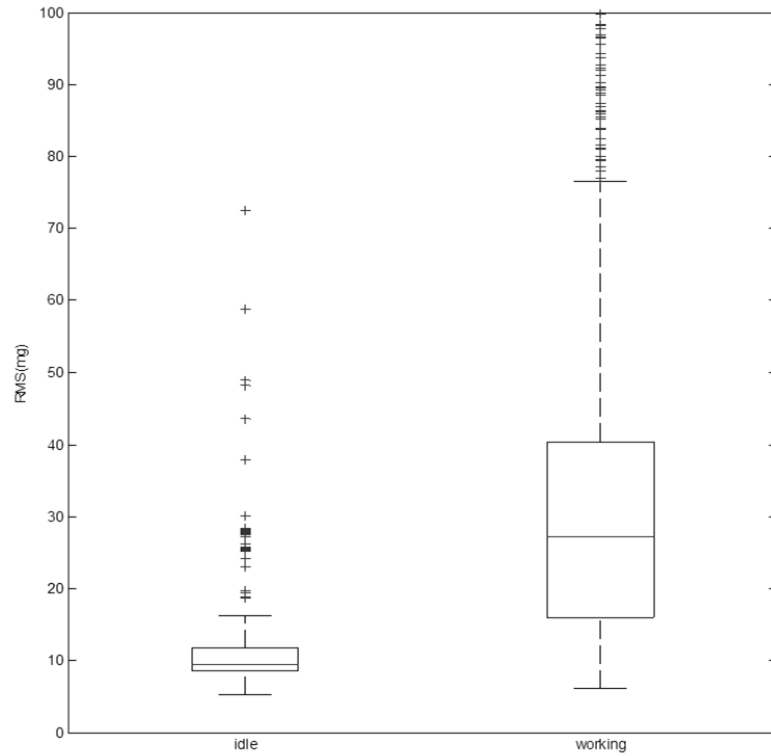


Figure 6.5. Box-plot of RMS values of working and idling modes of Case Study 1

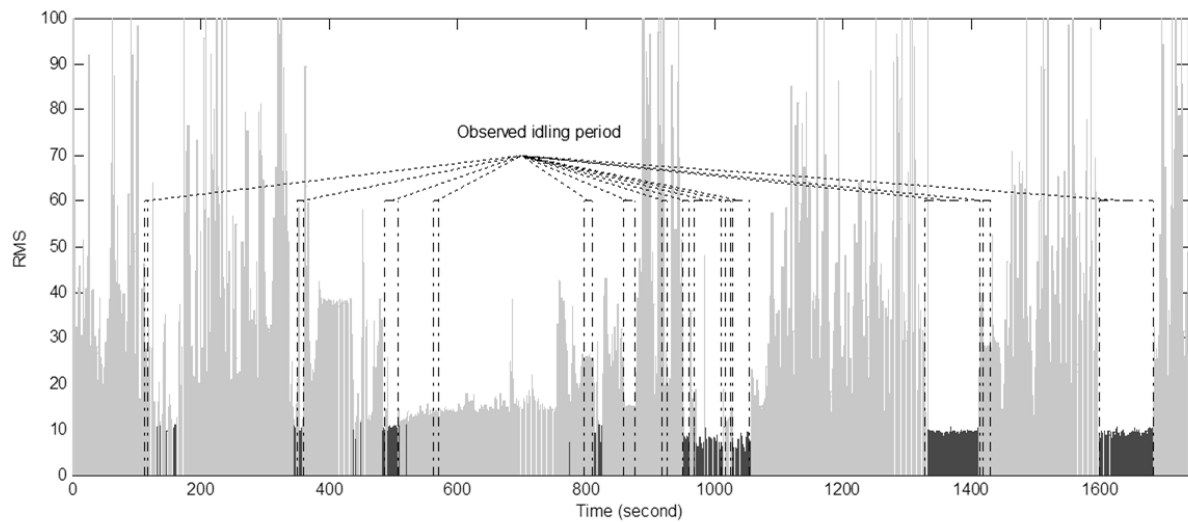


Figure 6.6. Comparison of idling periods between the observation (dotted-line box) and the energy analysis of vibration signals (dark gray bars) in Case Study 1

5.2. Case study 2

The second case study analyzed a medium-sized wheeled excavator that performs debris-clearing and destroys existing pavement. The difference of the undercarriage type is expected to affect vibration patterns and amplitude. In addition, the wheeled excavator is equipped with stabilizers to provide better lifting performance during stationary operating, and the use of the stabilizers would affect vibration patterns and amplitude. Two independent observations are made; one lasting around 30 minutes, the other around 60 minutes. During the first observation, the excavator mainly cleared and moved waste, and processed debris with another bobcat. During the second observation, the excavator mainly demolished existing ground pavement, with its stabilizers down. The sensor was installed for each observation, so the mounting location and orientation changed.

Figure 6.7 shows the time series data of the RMS value, and Figure 6.8 shows a box plot of the RMS distribution of the working and idle time frames in two observations. The statistical analysis using t-test ($P < 0.01$) confirms the difference of the RMS values between working and idle time frames in both observations. Another point of interest in this case study is whether and to what extent the change of mounting conditions (location and orientation) of the sensor affects the vibration amplitude (RMS values) of the idling time frames and the RMS threshold value for the classification. The first observation is found to have a difference in the RMS distribution of the idling time frames compared to the second observation, in terms of the interquartile range. However, they have a similar level of mean values and RMS threshold values that generate a minimum error rate. This indicates that a possible deviation of sensor mounting conditions may not significantly impact the accuracy of the classification.

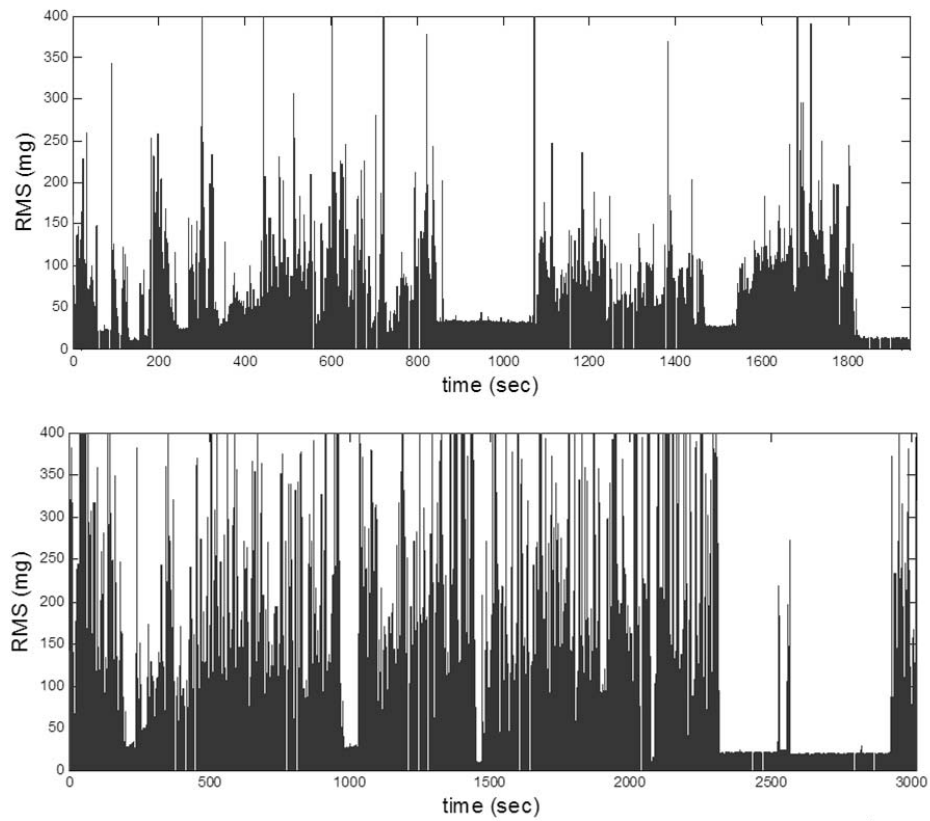


Figure 6.7. RMS time series of Case Study 2 – (top) 1st observation; (bottom) 2nd observation

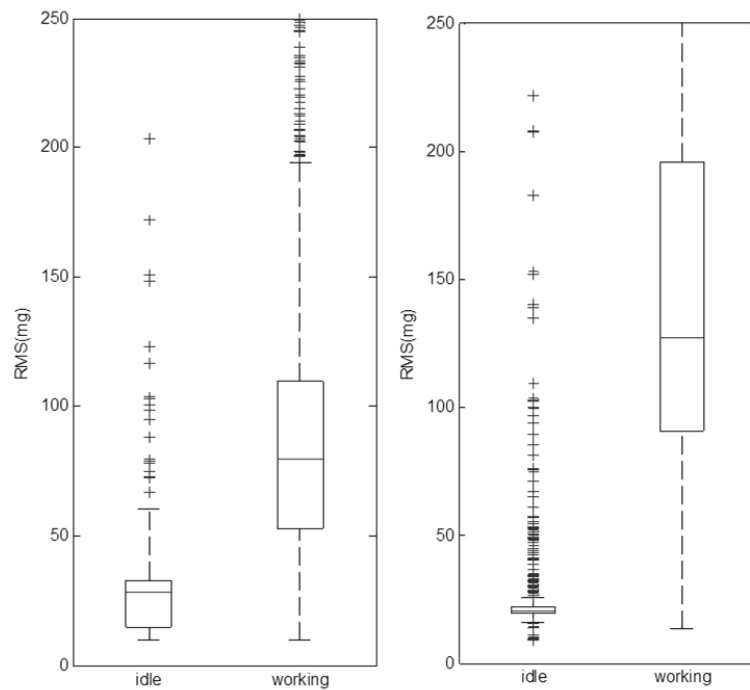


Figure 6.8. Box-plot of RMS values of working and idling modes of Case Study 2 – (left) 1st observation; (right) 2nd observation

The RMS threshold value that generates a minimum error rate is determined to be 35 mg and 36.5 mg in the first and second observations, respectively. Figure 6.9 shows the result of the classification using these RMS threshold values. The overall error rates in the first and second observations are assessed to be 9% and 4%, respectively, while the *working error* rates are assessed to be 9% and 2%, and the *idling error* rates 11% and 9%. The type of work that the equipment performs is found to affect the classification error rate. In this case study, the demolition work that involved actions with high engine torque and power output resulted in a better accuracy in the classification.

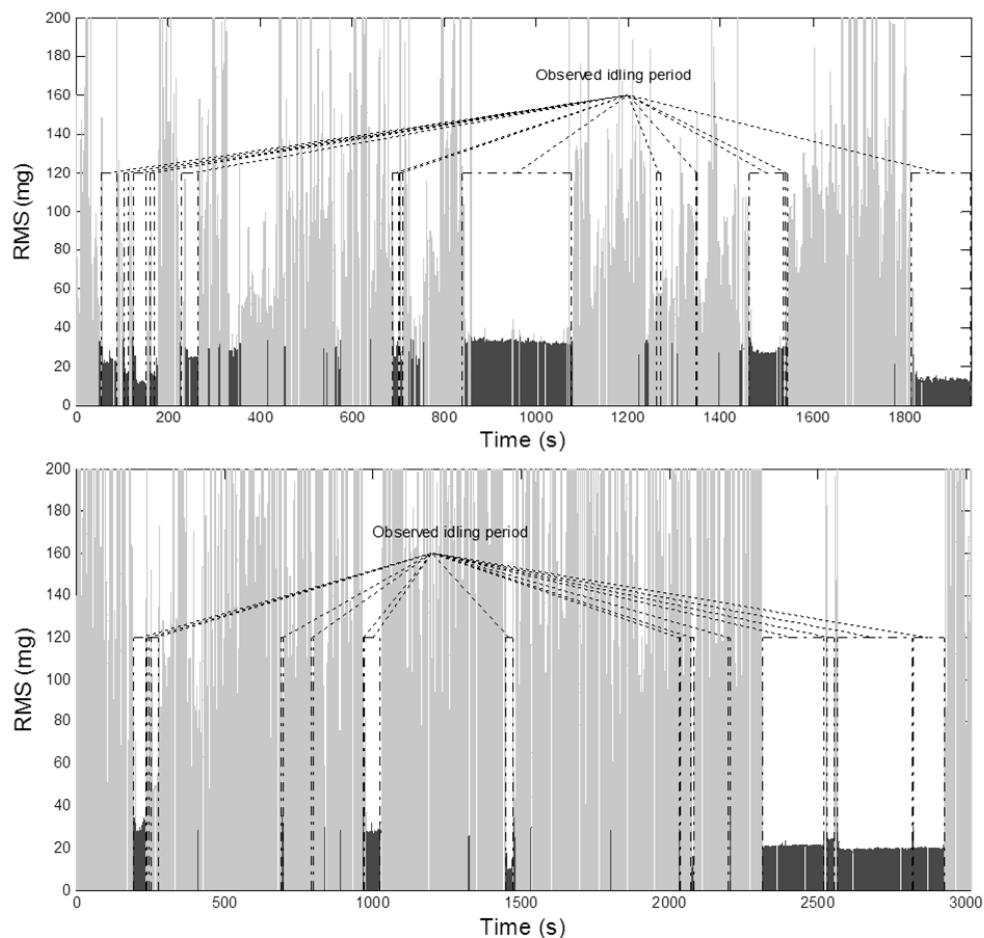


Figure 6.9. Comparison of idling periods between the observation (dotted-line box) and the energy analysis of vibration signals (dark gray bars) in Case Study 2 - (top) 1st observation; (bottom) 2nd observation

5.3. Case study 3

A large-sized excavator that bored holes for dewatering using a vibratory pile driver is chosen for the third case study. The performed work repeated the working cycle that consisted of moving, locating the pile driver, driving the pile, and pulling out the pile. While driving the pile generated an excessive level of vibration, moving and locating the pile driver involved a very modest level of vibration.

Figure 6.10 shows the time series data of the RMS value, and Figure 6.11 shows a box plot of the RMS distribution of the working and idle time frames in two observations. The difference of the RMS values between two groups is confirmed through a t-test ($P < 0.01$). The RMS threshold value that generates a minimum error rate is determined to be 73 mg, based on the previously described algorithm. Figure 6.12 shows the result of the classification using this RMS threshold value. The overall error rate is assessed to be 7%, while the *working error* rate is assessed to be 6%, and the *idling error* rate 10%. Locating and calibrating the pile driver at the start of each production cycle involves sporadic pauses of the excavator motion that caused a difficulty in the classification even with the visual observation. Those time frames were found to be error-prone.

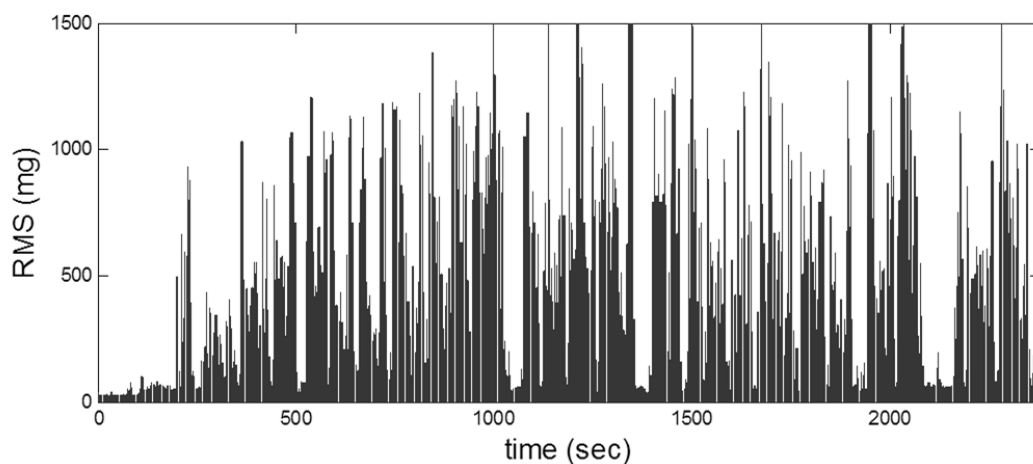


Figure 6.10. RMS time series of Case Study 3

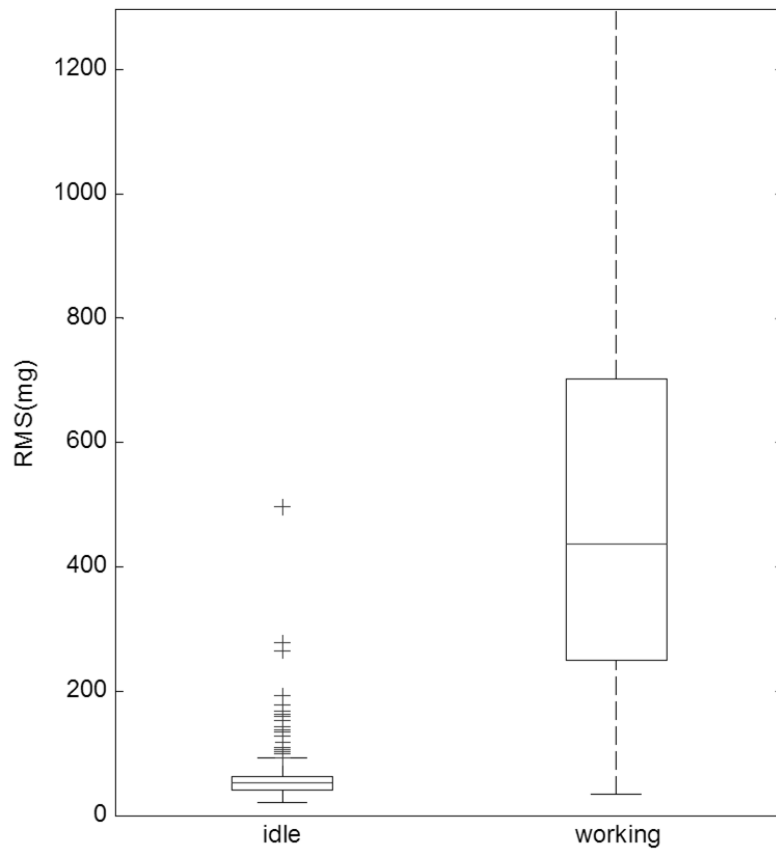


Figure 6.11. Box-plot of RMS values of working and idling modes of Case Study 3

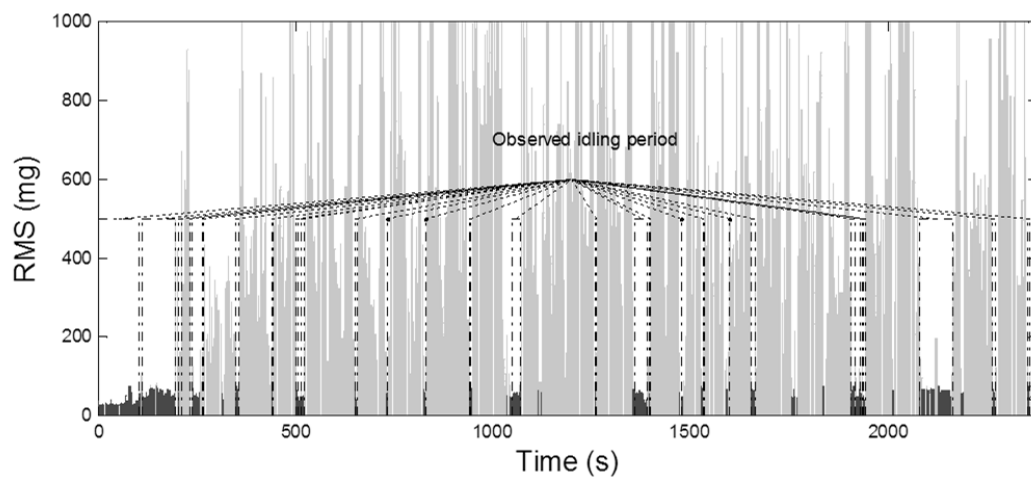


Figure 6.12. Comparison of idling periods between the observation (dotted-line box) and the energy analysis of vibration signals (dark gray bars) in Case Study 3

5.4. Results and Analyses

The primary focus of the case studies is on the detecting accuracy of the actual versus measured values of the operating equipment efficiency, which is the ratio of valuable operating time to total operating time. Table 6.2 summarizes the actual and measured operating equipment efficiency values of the case studies. The classification errors in the case studies created a deviation between the actual and measured operating equipment efficiency. However, such deviations are found to be quite small (within ± 3) compared to the classification error rates, because *working errors* and *idling errors* somewhat offset each other in the assessment of the operating equipment efficiency.

Table 6.2. Summary of case study results

	Equip. Specs. (HP, model year)	Performed Work	Classification Error (%)	Operating Equipment Efficiency		
				Actual	Measured	Deviation
Case 1	Crawler type, (148 hp, 2010)	Trench and install utility	8%	79%	81%	+2
Case 2	Wheeled type (160 hp, 2006)	1 st - Clear debris	10%	69%	66%	-3
		2 nd - Demolition	4%	74%	75%	+1
Case 3	Crawler type, (270 hp, 2004)	Drill dewatering holes	7%	80%	77%	-3

In addition, the classification errors can be greatly alleviated with a more practical definition of the idling period. In the case study, the manual observation determined that the excavator was idling if it did not show any physical movement for more than three seconds, regardless of its engine status. During idling, however, excavators' engines typically go through four sub-modes: low idle, transient between low and high idle, high idle, and transient between high idle and non-idle (Abolhasani et al. 2008). When the operator is ready to start using the bucket, he/she increases the engine idle speed to a high idle mode, which is run at a higher engine revolutions per minute (RPM) than a low idle mode. Therefore, during short idling periods, the excavator may have run at high idle or transient modes, rather than at a low idle

mode, whereas it may have run mostly at a low idle mode during long idling periods. This would explain a high error rate in detecting short idling periods, and a low error rate in detecting long idling periods. In a real-world operation, a three-second-long pause of the equipment motion often occurs between the change of motion (body direction or initiating boom use). In the case that we regard such short pauses as the continuation of the valuable operating, and define idling with a longer period of continuous motion pause, the accuracy of the classification would greatly improve, by allowing the discard of idle errors in short idling periods.

The signal produced by the accelerometer is dependent on the relative orientation of the accelerometer based on the direction of Earth's gravity. Integrating signals from three axes was expected to minimize the effect of the mounting orientation of the accelerometer, but failed to completely disregard such effect, since the detrend process of raw data and data floating limits creates a difference of steady state RMS values by the mounting orientation. Therefore, in the case that the equipment body tilts slightly during its operation, the baseline of vibration signals was affected and sometimes classification errors occurred. This type of error will be addressed with the use of another signal feature for the classification (e.g. kurtosis, crest factor) or the adoption of advanced signal processing techniques (e.g. spectral analysis). On the other hand, external noises (e.g. unintended knock on the sensor) created a spike in the signals and sometimes caused classification errors. This type of error can also be addressed with the use of filtering techniques, which can smooth out short-term fluctuations and highlight longer-term trends.

In summary, the level of classification errors found in the case studies is acceptable for an environmental monitoring application, since (1) the effects of this level of classification errors on the accuracy of measuring the operating equipment efficiency are not significant, and (2) the

classification errors would be greatly reduced with the practical definition of equipment idling. In addition, the accuracy of the classification can be greatly improved by using advanced signal processing techniques, although this chapter focused on evaluating the feasibility of the application of low-cost accelerometers based only on the simplest method.

6. CONCLUSIONS AND FUTURE IMPLEMENTATIONS

This chapter presented a system to measure the operational efficiency of equipment. Its feasibility in a real-world operation was demonstrated by assessing the accuracy in case studies. The presented approach has significant advantages over other emerging technologies: (1) it requires much less cost and effort to construct a comprehensive monitoring system for many pieces of equipment employed in a large-scale project; (2) it ensures compatibility with any equipment, regardless of age or manufacturer; and (3) it provides a non-intrusive measure so that its application is met by minimal resistance from subcontractors and equipment owners. Also, this method has an advantage over Global Positioning System (GPS)-based monitoring, in that it can detect the operation of construction equipment in a stationary mode. The presented approach will potentially offer a significant contribution to the enhancement of productivity monitoring, as well as environmental performance monitoring.

Figure 6.13 illustrates a visualized report of environmental performance monitoring with the future implementation of the proposed system. In the report, the daily OEEs of each piece of equipment are measured by accelerometers and presented. Based on the measured daily OEEs, average OEEs are presented, and the deviations are quantified based on the target value of OEEs that are set by the predictive assessment model. In addition, based on the measured OEE values, the amount of each type of air pollutant emitted daily and cumulatively is assessed using the emission factors of each piece of equipment. The deviation between the target value and actual

value of emission amount is also presented. This envisioned use of the proposed system will help construction stakeholders understand the environmental performance of on-going operations, and will allow them to take timely actions in order to improve performance.

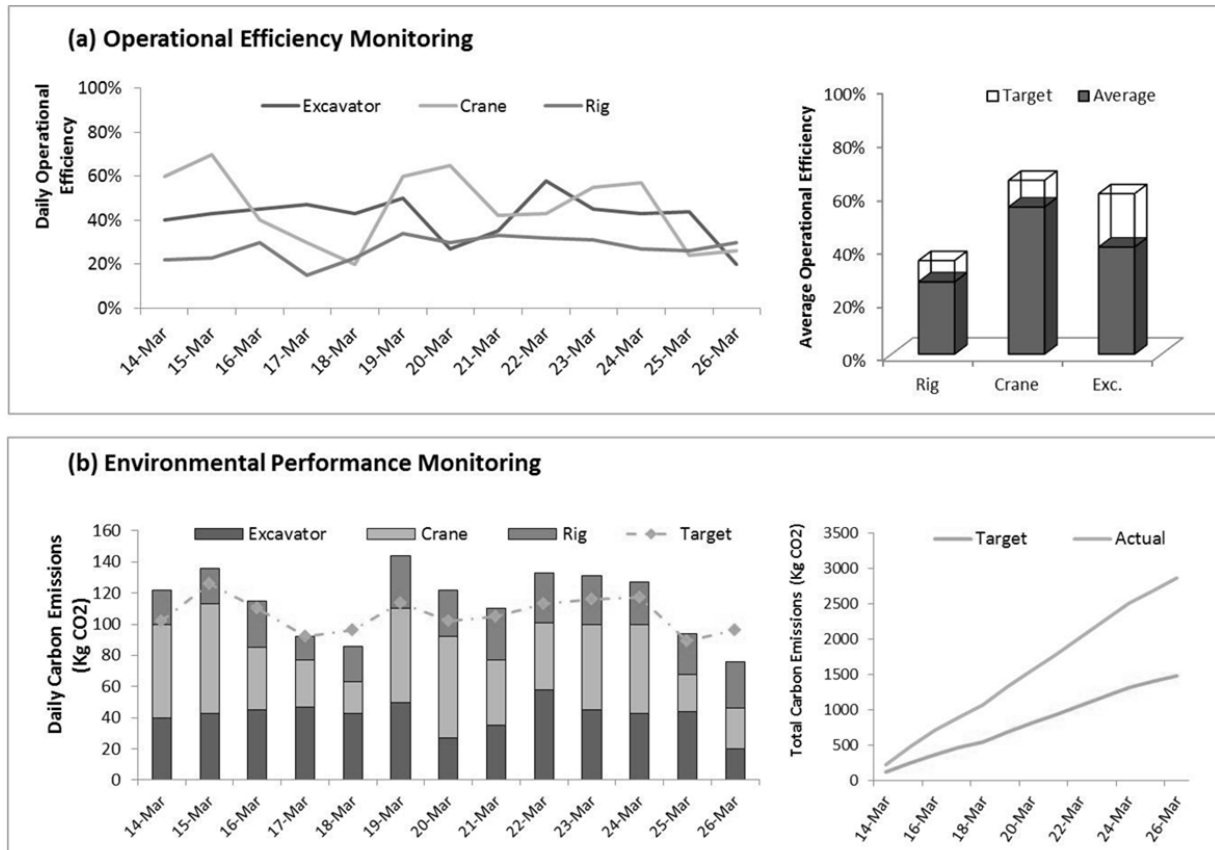


Figure 6.13. Environmental performance monitoring report: (a) measured daily and average operational efficiencies of in-use construction equipment, (b) tracked daily and cumulative emission amount from the project.

CHAPTER 7

CONCLUSIONS

1. CONCLUSIONS

Over the years, efforts toward environmental sustainability in the building and construction sector have focused on improving the environmental performance of the sector's products (buildings and civil infrastructure, e.g.). In contrast, the environmental impact of the processes used to construct these products has largely been ignored, even though these processes constitute significant economic activity. Construction processes account for a substantial amount of Greenhouse Gas (GHG) and other diesel exhaust emissions, including NO_x and PM. The adoption of environmentally conscious practices in construction projects would thus substantially reduce aggregate emissions. However, the shift toward environmentally conscious practices, in terms of energy consumption and associated exhaust air emissions, remains slow.

One reason for this slowness may be a lack of motivation mechanisms that encourage contractors to take steps that go beyond compliance with current environmental regulations, which are insufficient for controlling the environmental impact of energy consumption and air pollutant emissions from construction processes. On the contrary, clients of construction projects, in particular public clients, are under pressure from environmentally conscious stakeholders, and so seek a way to demonstrate their environmental commitment. The challenge that these clients have, then, is a technical one—how to evaluate the green capabilities of contractors who allow fewer air pollutant emissions to be generated by construction operations.

Another reason that the shift toward better practices has been slow is that contractors lack

appropriate methods and tools to assess and monitor the environmental performance of their day-to-day operations (in terms of energy consumption and associated exhaust air emissions). Planning and control decisions that are related to resource allocations and scheduling in daily construction would affect the environmental performance of a project, but existing environmental impact assessment models cannot incorporate such effects. In addition, a formal methodology that measures the actual environmental impact caused by operational decisions during construction is not in place.

To address these challenges, this dissertation has established an integrated management framework. This framework includes the evaluation of the green capabilities of contractors at the bidding and contracting stage, the predictive assessment of the environmental performance at the planning stage, and the outcome assessment of the environmental performance at the construction stage. The requirements of each module of the framework are analyzed and presented, based on an understanding of the determinants of the environmental performance of construction operations. The green capabilities of contractors are largely related to the environmental properties (fuel efficiency of equipment and emission intensity of fuel) of the legacy equipment fleets of contractors. Once the environmental properties of resources and fuel are determined at the contracting stage, the operational efficiency is the most important factor to be measured and controlled at the planning and construction stages.

The evaluation method of contractors' green capabilities that is presented in this work assesses the potential energy consumption and emission generation of contractors' legacy equipment fleets. It also calculates a single indicator that incorporates various types of environmental impacts (energy use, CO₂, PM, NO_x, and other air pollutants), using the standardized monetary cost index of the environmental impact. Also proposed is the bidding

methods that include the environmental cost produced by the contractors' equipment fleets in the bid evaluation process. The impact on the contract award under the proposed bidding methods—made by contractors' adoption of possible emission mitigation measures (mostly, technical strategies)—is then assessed using the case study. The result of the case study has demonstrated that including the environmental cost in the bid evaluation can be an effective motivation mechanism in creating contractors' effort to mitigate the environmental impact caused by their construction operations.

The predictive assessment model of environmental performance that is presented in this work integrates the analysis of the operational efficiency into the environmental impact assessment of construction operations. The case studies have demonstrated that a change in resource allocation and scheduling significantly impacts the environmental performance by affecting the operational efficiency of resources. The presented predictive assessment model has evaluated such impact in the case studies. The result of the case study has also indicated that an operational strategy, such as the adjustment of resource allocation and scheduling, can significantly reduce air pollutant emissions without a notable adverse effect on cost or schedule.

The outcome assessment system of environmental performance that is presented in this work monitors the environmental performance by tracking the operational efficiency of each piece of equipment during construction. The presented system utilizes low-cost accelerometers to measure the operational efficiency of construction equipment. The feasibility of the system in a real-world operation of excavators has been examined through case studies. The deviations between the actual and measured operational efficiencies in the case studies are reported to be in the acceptable range for the practical applications.

The deployment of the management framework and supporting methods/tools that are

described in this dissertation allows construction stakeholders to identify the mitigation opportunities for energy use and emission generation in their operations, thereby meeting the growing need of environmentally conscious stakeholders (e.g., public agencies, society, government) for sustainable infrastructure development. Further, a baseline on energy use and air pollutant emissions—which allows managers to easily identify energy and emission levels, and to take timely actions—has not truly been defined for construction operations due to the complexity and unique qualities of the industry. The deployment of the framework can thus contribute greatly to diverse opportunities for sustainable infrastructure development by providing an energy and air pollutant baseline. This would prepare the construction industry for the risk of future regulatory actions that will have direct and indirect effects on the daily operations of contractors. Further, the deployment of the framework would allow the industry to proactively address growing pressure from environmentally conscious stakeholders.

2. CONTRIBUTIONS

The main research contributions of this work can be summarized as follows:

1. The opportunities and challenges for the reduction of energy consumption and air emissions for the construction industry have been identified in Chapter 2. The main sources of energy consumption and air emissions in construction operations have been analyzed, and existing regulatory and voluntary efforts to control those sources have been reviewed. The review highlights that existing efforts have centered mostly on implementing technological strategies that upgrade the environmental properties of legacy construction equipment; the environmental commitment of public entities is the main driver of these efforts. In addition, it has been identified that the operational strategies have great potential to reduce air pollutant emissions, as well as energy

consumption. Further, the operational strategies offer these benefits with less additional cost than the technological strategies would.

2. Key factors that determine the environmental performance of construction operations have been revealed in Chapter 3, and the requirements for controlling key factors have been identified. These key factors include the operational efficiency of a process, the fuel efficiency of a resource, and the emission intensity of fuel. The fuel efficiency of a resource and the emission intensity of fuel are determined to be key parameters for evaluating the green capabilities of contractors at the bidding and contracting stage. The link between the operational efficiency and the environmental performance, which is revealed in Chapters 3 and 5, is important for understanding how and to what extent operational decisions on resource allocation and schedule affect the environmental performance.
3. The evaluation method of the green capabilities of contractors is developed and integrated into a multi-parameter bidding system in Chapter 4. Considering the environmental cost to be incurred by contractors' operations as a criterion for awarding contracts encourages contractors to seek cleaner construction equipment, methods, and processes, moving beyond the incentives merely to account for and monitor construction emissions from a given project. With this bidding method, the client (predominately public entities in these scenarios, but also private entities) would be able to show stakeholders and end-users its commitment to the environment, achieving a green project delivery and maintaining a competitive advantage in an increasingly green market. Furthermore, the consideration of construction emissions in contracting would allow public clients to effectively control construction emissions from their contractors. This

would allow public clients to adequately address current and future regulations requiring them to inventory and reduce their emissions.

4. The environmental impact assessment model of construction operations, which enables the consideration of the variability of the operational efficiency due to different project characteristics and operation plans, is formulated and implemented in Chapter 5. With this model, construction stakeholders will be better informed about the potential environmental impact of their decisions in the planning phase of operations. Such consideration of environmental aspects in planning helps construction managers identify an option that will increase the project's "integrated-value," which includes schedule, cost, and environmental impact. Furthermore, this model will allow project managers to set baselines to monitor performance and prevent and mitigate any environmental impact of their construction operations.
5. The monitoring system to track the operational efficiency of construction equipment is developed with an economically feasible technology, and is tested, in Chapter 6. The approach to measure the operational efficiency of construction equipment using an accelerometer has clear advantages over other approaches (GPS-based and vision-based monitoring systems, e.g.) in terms of technological capabilities in the detection of equipment operation, as well as the economic feasibility of implementation. The monitoring of the operational efficiency enables construction stakeholders to measure the environmental performance of day-to-day operations and to take timely actions in order to improve the environmental performance. In addition, the development of an automated economically feasible monitoring system of the operational efficiency will contribute not only to improving the environmental performance, but also to helping monitor and

enhance the productivity of overall operations by detecting excessive non-valuable operation.

3. RECOMMENDATIONS FOR FUTURE RESEARCH

The management framework and supporting methods/tools presented in this dissertation have the potential to address current technical challenges associated with the implementation of environmentally sustainable construction processes. However, many issues still need to be resolved for the effective implementation of the proposed framework and supporting methods/tools.

1. In order to successfully and fully implement the evaluation of the green capabilities of contractors, the environmental cost index needs to be further investigated to determine the optimum price level at which contractors are encouraged to pursue meaningful efforts to develop greener construction methods. Within this investigation, the price should not distort the bidding process by placing excessive weight on the emissions portion of a bid within the A+C and A+B+C bidding methods. In addition, reliable methods and procedures to develop a bid on construction emissions, and to verify the actual emissions, need to be developed to create a level playing field for all bidders.
2. Fuel use and emission rates that can be linked to different operation modes of construction equipment need to be further investigated. In this study, emission rates for non-idle and idle modes were determined using some representative data rather than equipment-specific data. This was done because data is limited on the fuel use and emission rates that can be linked to different operation modes of a variety of construction equipment. Thus, additional research is required to build a database of fuel use and

emission rates that can be expandable to commonly used construction equipment with various engine sizes, model years, and hours of use.

3. There is a need to examine factors that affect the idle rate of equipment. This examination should happen through further investigation of equipment usage patterns related to the operating equipment efficiencies (OEEs) found in various types of construction operations. This will allow us to set goals for the OEEs of construction equipment based on various factors of a project. Further, this will allow us to evaluate the environmental performance based on our goals.
4. In regard to measuring the operational efficiency of construction equipment by using signals captured from accelerometers, there exist great opportunities for improving the accuracy and minimizing the training process. The current approach in the classification of second-by-second equipment operation mainly depends on one feature of the signals for the purpose of testing the approach's feasibility. However, utilizing multiple features of signals could greatly improve the accuracy of the classification. In addition, the current approach is based on supervised learning that requires a training process, and this would cause the calibration process for each piece of construction equipment. The development of a classification algorithm based on unsupervised learning has the potential to minimize the training process of the monitoring system.
5. The relationship between the OEEs (measured using accelerometers) and the emission amounts needs to be examined and verified. Previous studies (Lewis et al. 2011a; Lewis et al. 2011b) have examined the impact of the operational efficiency on the emissions of a piece of equipment, and have provided the method to quantify an additional emission amount according to the OEE. However, due to possible errors in measuring OEEs using

accelerometers, the uncertainty of the emission estimation based on the measured operational efficiency needs to be reassessed. For this purpose, there must be a comparison between the emission estimates based on measured operational efficiency and the actual emission amount measured by Portable Emission Measurement Systems (PEMS).

6. While this dissertation focused on the reduction of the environmental impact incurred by on-site construction activities and large-quantity material transportation from final suppliers to jobsites, there is also a great potential to reduce the environmental impact incurred by the entire supply chain of construction materials; this chain includes material handling and distribution at each step, from raw materials to finished products for on-site installation. The consideration of the environmental impact of the supply chain in contracting practices will thus create a bigger impact on the improvement of the environmental performance of the construction industry. For example, including the environmental impact of the material supply chain in the C bid under the A+C bidding method will greatly promote contractors' use of locally-sourced and recycled material, such that contractors go beyond their current voluntary efforts. In this context, future research is recommended to develop a method to holistically quantify the environmental impact from the construction material supply chain in a relatively simple manner, and to establish a procedure to track data for analyzing the environmental impact from the supply chain.

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