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RESEARCH ARTICLE

Hakob AVETISYAN, Miroslaw SKIBNIEWSKI, Mohammad MOZAFFARPOUR

Analyzing sustainability of construction equipment in the state of California

Abstract Construction equipment encompasses highly polluting machines adversely affecting the environment. Management tools are necessary for sustainability assessment of construction equipment fleets to allow contractors to reduce their emissions and comply with local or federal regulations. In addition to management tools, there is a need for a metrics that will allow companies to accurately assess the sustainability of their construction equipment fleets. The State of California USA is adopting innovative approaches to reduce adverse impact of humans on the environment. Once successfully implemented, the chances are that such practices attract other states to adopt similar approaches. This paper presents an evaluation of construction equipment fleets and data analysis. When measured and recorded, such results can be used along with decision-support tools for selection and utilization of construction equipment. The metrics for construction equipment evaluation as well as the tool for sustainable decision-making are developed based on readily available data from manufacturers or maintenance shops without a need for additional effort by contractors or government agencies for their adoption. The metrics developed and the decision support tool incorporate logical strategies of supply chain management for optimal selection of construction equipment for construction site while taking into account the availability, cost, and mobilization related constraints. The metrics and the model can benefit both the government agencies responsible for inspection of fleets and owners of construction companies in their decision-making processes related to environmental sustainability.

Keywords Construction equipment, greenhouse gas emissions, sustainability index, sustainable construction

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Hakob AVETISYAN (✉), Mohammad MOZAFFARPOUR
Department of Civil and Environmental Engineering, E-209, 800 N. State College Blvd, California State University Fullerton, CA 92834, USA
E-mail: havetisyan@fullerton.edu

Miroslaw SKIBNIEWSKI
Department of Civil and Environmental Engineering, Glenn L. Martin Hall 1188, University of Maryland College Park, MD 20742, USA

1 Introduction

The State of California has been traditionally known for development, testing and implementation of environmental regulations and policies aimed at providing and promoting sustainable practices. Similar regulations have been developed for construction equipment emission level reductions. Nationwide, these regulations were enacted from multiple perspectives targeting not only the manufacturers' side of the problem who were forced to improve engine and filtration technologies over defined time intervals, but also from the perspective of physical limitations enforced on the construction sites (ARB, 2007, 2010a, 2010b).

The State of California was the first state in the USA that in June, 2007 adopted a regulation aimed at reducing diesel emissions from construction equipment operating on construction sites (UCSUSA, 2015). By 2020 this rule requires the owners of off-road equipment such as tractors, bulldozers, and forklifts that use diesel fuel to reduce emissions from the operation of this equipment. The expected outcome of such a requirement is a reduction and elimination of adverse impact of emissions on human health. Such impacts include, but are not limited to premature deaths, asthma attacks, and hospitalizations due to heart and/or lung disease.

The construction industry adds a significant amount of greenhouse gas (GHG) emissions into the atmosphere. In a large part, these emissions are due to construction equipment, which is similar to on-road vehicles in the sense of its dependence on fossil fuels as an energy source. Demand for different fossil fuel types continues, which results in an increase in GHG emission levels as predicted by EPA (2009a), where the construction industry is thought to be the third largest emitters (EPA, 2009b).

Construction equipment, if periodically maintained, can past 30 years or more, and its adverse effect on the environment needs to be considered in decision-making. During the lifetime of construction equipment, the environmental impact can be disturbing if no upgrades with exhaust controls or replacement with new engines are applied or equipment fleets are not replaced with newer and less polluting models. On average, when compared to a regular passenger car, all construction equipment generate much higher levels of emissions. Different factors such as the fuel type, engine technology, as well as horsepower, make a significant difference in the amount of emissions generated. For example, a typical excavator produces 454 pounds of carbon dioxide per hour of operation. In contrast, a typical medium-sized passenger vehicle produces 55 pounds of carbon dioxide per hour of operation. In one year, considering a typical 2000 h of operation it turns to 454 tons of carbon dioxide equivalents just from one excavator. If equipment is not well maintained, the amount of emissions generated per a piece of equipment increases even further. Therefore, it is imperative for any contractor managing a large construction fleet to find problems in equipment management in advance both at operational as well as at corporate levels. Commonly, without even taking into consideration the possibility of improving the system, an equipment manager is likely to concentrate on problems only after the fact that there is something obviously wrong (Fan et al., 2008). As a consequence, the contractors face higher and still growing costs and inefficiencies.

To understand an overall sustainability of construction equipment fleets, it is important to develop a common measure that can be easily applied and help decision-makers. For this purpose, a method that links the age of equipment and the power of an engine has been developed. The next section presents the development and the reasoning of applied approach.

2 Sustainability measure

The sustainability of construction equipment can be assessed in a variety of ways. In this paper, a Sustainability Index (SI) is introduced as one of the ways to analyze the sustainability of construction equipment. The SI is calculated as a result of the combination of the age of the equipment and its engine power. These two parameters impact the amount of generated emissions from construction equipment. The reason for such linkage between the amount of generated emissions and the age combined with engine power is the engine technology that is being developed year after year.

To control the amount of emissions, regulations and policies are being developed and implemented in industries. As a result of such movement, engine technologies are being developed as well. Stricter regulations and requirements enforced by policy-makers limit the amount of emissions that can be generated by on-road and/or off-road engines. Therefore, limits have been set for certain years which should be met by construction equipment manufacturers.

Emission limitations vary by the type of pollutant and the engine power. In 1998 off-road engine emission regulations were developed to a 3 Tier level system. Over the years Tiers were phased-in (based on power rating). As such, Tier level 1 was applied to equipment manufactured between 1996 and 2000. Much stricter Tier level 2 came in effect for years between 2001 and 2006. Similarly, Tier level 3 was applied between 2006 and 2008 which was more stringent than Tier level 1 and 2. In fact, Tier level 1 was applied to engines between 37 and 560 kW. In practice, the engine power is rated by kilowatts per hour, but is also converted to horsepower. Tiers 1 to 3 for emission standards are presented in Table 1.

There are also Tier 4 standards that have more stringent requirements for NO_x emissions, but the requirements are practically the same on the amount of CO and PM emissions generated by off-road engines and therefore it is not presented in the form of a table. In a summarized form, the requirement for NO_x emissions is reduced to 0.4 from 9.2 that should be met by off-road equipment produced between 2011 and 2014 (DieselNet, 2013). The variations in requirements per emission type make it difficult to assess and compare the changes that come with technology developments, which may assist in evaluating the sustainability of equipment fleets. Therefore, a unified method was developed as a combination of equipment age and engine power by averaging the impact of retrofitting. As such, the results are presented in Table 2.

In Table 2 the first column is the year of equipment manufacture followed by a column for age counted based on the benchmarking year of 2015 for the current state. The third column in the table is for horsepower and as a sample case, the 750 is used for comparison, which works equally well for any other horsepower ranges. The column titled A&HP represents the combination of the age and the horsepower of the engine. The development of engine technology is not and has never been linear and therefore a square root of A&HP was calculated and then normalized in order to obtain to zero and unit value for extreme value ranges. In fact, if pay attention to the SI value for 2015 of 0.82 it means that the improvement potential is not completely achieved. This also matches with the real world situation where the regulations are still enforcing further improvements for emission reductions by engine technology advancements. As such, EU Regulation No 443/2009 sets an average CO_2 equivalent reduction for commercial vehicles to 175 g/km by 2017 then 145 g/km by 2020 a

Table 1 EPA Tier 1 to 3 non-road diesel engine emission standards in g/kWh (g/bhp·h) (Source: https://www.dieselnet.com/standards/us/nonroad.php)

Engine power	Tier	Year	CO	HC	NMHC + NO_x	NO_x	PM
kW < 8	Tier 1	2000	8.0 (6.0)	-	10.5 (7.8)	-	1.0 (0.75)
(hp < 11)	Tier 2	2005	8.0 (6.0)	-	7.5 (5.6)	-	0.8 (0.6)
8 ⩽ kW < 19	Tier 1	2000	6.6 (4.9)	-	9.5 (7.1)	-	0.8 (0.6)
(11 ⩽ hp < 25)	Tier 2	2005	6.6 (4.9)	-	7.5 (5.6)	-	0.8 (0.6)
19 ⩽ kW < 37	Tier 1	1999	5.5 (4.1)	-	9.5 (7.1)	-	0.8 (0.6)
(25 ⩽ hp < 50)	Tier 2	2004	5.5 (4.1)	-	7.5 (5.6)	-	0.6 (0.45)
37 ⩽ kW < 75	Tier 1	1998	-	-	-	9.2 (6.9)	-
(50 ⩽ hp < 100)	Tier 2	2004	5.0 (3.7)	-	7.5 (5.6)	-	0.4 (0.3)
	Tier 3	2008	5.0 (3.7)	-	4.7 (3.5)	-	-†
75 ⩽ kW < 130	Tier 1	1997	-	-	-	9.2 (6.9)	-
(100 ⩽ hp < 175)	Tier 2	2003	5.0 (3.7)	-	6.6 (4.9)	-	0.3 (0.22)
	Tier 3	2007	5.0 (3.7)	-	4.0 (3.0)	-	-†
130 ⩽ kW < 225	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
(175 ⩽ hp < 300)	Tier 2	2003	3.5 (2.6)	-	6.6 (4.9)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
225 ⩽ kW < 450	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
(300 ⩽ hp < 600)	Tier 2	2001	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
450 ⩽ kW < 560	Tier 1	1996	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
(600 ⩽ hp < 750)	Tier 2	2002	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)
	Tier 3	2006	3.5 (2.6)	-	4.0 (3.0)	-	-†
kW ⩾ 560	Tier 1	2000	11.4 (8.5)	1.3 (1.0)	-	9.2 (6.9)	0.54 (0.4)
(hp ⩾ 750)	Tier 2	2006	3.5 (2.6)	-	6.4 (4.8)	-	0.2 (0.15)

further reduction of 28%. In the US the reductions comparisons from Table 1 indicate that if, for example, the average reduction is calculated for 750 horsepower from years 1996 to 2006 the improvement of 44% can be noticed. This means that another 56% improvement is still possible. Based on the SI calculation the year 2006 shows 42% and for 2007 45% meaning that the 55% to 58% improvement can be still anticipated if the 100% is ever achievable.

Table 2 is considering the age of up to 30 years old equipment, but the same approach can be applied if there is an even older piece of equipment under consideration.

To show the results of the SI on a graph, Fig. 1 is presented.

Figure 1 shows the relationship of the age of an equipment piece that has the 750 HP engine and the SI calculated as described in the discussion of Table 2. Similarly, any engine power at any age can be analyzed that will help in measuring the sustainability of the construction equipment fleets. Such approach may aid fleet managers and policy-makers in decision-making for more reasonable requirements for construction sites as imposed by Environmental Protection Agency (Avetisyan et al., 2012).

Once the metric for measuring the sustainability of construction equipment is defined, it can be used together with decision support tools and models for deciding what equipment and when to use or purchase for a long-term business planning. This approach is applied to a decision support model developed by Avetisyan and Skibniewski (2014) that helps in the web-based management of construction equipment. The additions to the model are presented below, but for details, the reader is referred to Avetisyan et al. (2012) and Avetisyan and Skibniewski (2014) for other constraints and related explanation.

3 Mathematical model

In addition to the existing objective function and constraints, a new element is added to the objective function and a constraint to count for the SI of equipment and power needed for completion of construction tasks. In many instances, the decision for selecting construction

Table 2 Sustainability Index of achievements and the range of possible improvements

Year of manufacture	Age	Horsepower	A&HP	SQRT of A&HP	NSQRT of A&HP	Sustainability Index
2015	1	750	750	27.39	0.18	0.82
2014	2	750	1500	38.73	0.26	0.74
2013	3	750	2250	47.43	0.32	0.68
2012	4	750	3000	54.77	0.37	0.63
2011	5	750	3750	61.24	0.41	0.59
2010	6	750	4500	67.08	0.45	0.55
2009	7	750	5250	72.46	0.48	0.52
2008	8	750	6000	77.46	0.52	0.48
2007	9	750	6750	82.16	0.55	0.45
2006	10	750	7500	86.60	0.58	0.42
2005	11	750	8250	90.83	0.61	0.39
2004	12	750	9000	94.87	0.63	0.37
2003	13	750	9750	98.74	0.66	0.34
2002	14	750	10,500	102.47	0.68	0.32
2001	15	750	11,250	106.07	0.71	0.29
2000	16	750	12,000	109.54	0.73	0.27
1999	17	750	12,750	112.92	0.75	0.25
1998	18	750	13,500	116.19	0.77	0.23
1997	19	750	14,250	119.37	0.80	0.20
1996	20	750	15,000	122.47	0.82	0.18
1995	21	750	15,750	125.50	0.84	0.16
1994	22	750	16,500	128.45	0.86	0.14
1993	23	750	17,250	131.34	0.88	0.12
1992	24	750	18,000	134.16	0.89	0.11
1991	25	750	18,750	136.93	0.91	0.09
1990	26	750	19,500	139.64	0.93	0.07
1989	27	750	20,250	142.30	0.95	0.05
1988	28	750	21,000	144.91	0.97	0.03
1987	29	750	21,750	147.48	0.98	0.02
1986	30	750	22,500	150.00	1.00	0.00

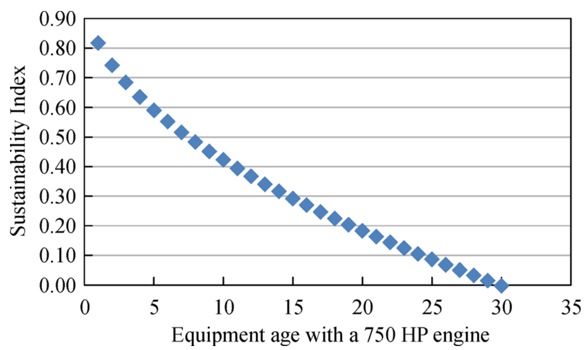

Fig. 1 Graphical representation of the Sustainability Index for a 750 HP equipment by year

equipment is made based on the capacity of the equipment without consideration of power requirements for a particular task. As a result, in many cases the equipment can be assigned to a particular task that exceeds the needs for the power more than twice that is necessary to complete the job. One may argue that if the task is not difficult, then the maximum power of the equipment will not be used even if a powerful machine is assigned. In fact, there is a difference when using a powerful machine for the low capacity task instead of the right power equipment. Even the idling of a powerful machine is more costly than that of a smaller piece of equipment.

The objective function and added constraint details in the model and notation are presented next.

The model

Notation employed in the mathematical formulation of the WB-CEMS's objective function are defined next.

J = Set of origin sites where the contractor operates

K = Set of destination sites where the contractor operates

X = {0,1,2,3}, set of all considered Tier levels

Y = Set of equipment types to be considered (e.g. excavators, tractors, loaders)

c_{xyjk} = Cost of operating (or renting, leasing as well as owning) each type of considered equipment $y\in Y$ in Tier $x\in X$, at site jk, $j\in J$, $k\in K$

cm_{xyjk} = Cost of moving each type of considered equipment $y\in Y$ in Tier $x\in X$, from site j site k, $j\in J$, $k\in K$

g_{xyjk} = GHG emissions rate for equipment type $y\in Y$, in Tier $x\in X$, at site jk, $j\in J$, $k\in K$, expressed in CO_2e

$wjkt$ = Number of working days at site jk, $j\in J$, $k\in K$, in any period $t\in S$

βjkt = Discounting factor for inflation at site jk, $j\in J$, $k\in K$, by period $t\in S$

Decision variables

α_{xyjkt} = Number of equipment pieces of type y, $y\in Y$, belonging to Tier level x, $x\in X$, at site jk, $j\in J$, $k\in K$, to be utilized during period $t\in S$

Formulation WB-CEMS

$$\text{Minimize } Z(\alpha_{xyjkt}) = [Z_1(\alpha_{xyjkt}),\ Z_2(\alpha_{xyjkt}),\ Z_3(\alpha_{xyjkt})] \tag{1}$$

In the objective function each of the Z functions is as the following:

$$Z_1 = \text{Min}\sum_{t\in s}\left[\sum_{x\in X}\sum_{y\in Y}\sum_{j\in J}\sum_{k\in K} c_{xyjk}\cdot\alpha_{xyjkt}\right]\cdot\beta_{jkt} \tag{1a}$$

$$Z_2 = \text{Min}\sum_{t\in s}\left[\sum_{x\in X}\sum_{y\in Y}\sum_{j\in J}\sum_{k\in K} w_{jkt}\cdot g_{xyjk}\cdot a_{xyjkt}\right] \tag{1b}$$

$$Z_3 = \text{Min}\sum_{t\in s}\left[\sum_{x\in X}\sum_{y\in Y}\sum_{j\in J}\sum_{k\in K} cm_{xyjk}\cdot\alpha_{xyjkt}\right]\cdot\beta_{jkt} \tag{1c}$$

$$Z_4 = \text{Min}\sum_{t\in s}\left[\sum_{x\in X}\sum_{y\in Y}\sum_{j\in J}\sum_{k\in K} (-SI_{xyjk})\cdot a_{xyjkt}\right] \tag{1d}$$

The set of constraints is not presented in this paper, and only conceptually discussed in this paragraph. The first, objective (1a), identifies needed equipment so as to minimize the total cost associated with completing construction projects under consideration. The second, objective (1b), minimizes emissions in terms of CO_{2e} generated during the construction equipment from all considered construction sites. The third objective (1c) minimizes the costs from moving equipment from one construction site to another. The fourth objective (1d) counts for the SI. Objective (1d) maximizes the SI, but due to the modeling consistency, it is presented as minimization of the negative of the maximization function. The constraints of the model are grouped into three general categories: those that control construction activity requirements, those that control emissions limitations, and budgetary caps related to the movement of equipment or the operation and ownership costs.

Similarly, a constraint is added to meet the power needs for each task:

$$\sum_{x\in X}\sum_{y\in Y}\sum_{j\in J}\sum_{k\in K} EHP_{xyjk}\cdot\alpha_{xyjkt} \geqslant THP_{xyjk}$$

$$\forall t\in S,\ i\in \mathrm{A}(\mathrm{I}')$$

where EHP_{xyjk} stands for the equipment horsepower and THP_{xyjk} for task required horsepower.

4 Practical application

The outcome of this research as a mathematical model was applied to a real life project in the construction industry. Type of contract for the project is Design-Build and the project size is about 70 million dollars. Clark Construction is the general contractor for this project, and the information that was provided by the contractor included time schedule, budgetary information, general project information. The 90,000 square-foot building will be comprised of teaching laboratories and flexible research space to accommodate a range of engineering and science programs. The project team also will construct a courtyard for interactive learning and to hold campus events. This project is designed to achieve LEED certification and therefore any sustainability-related improvement is important.

4.1 Assumptions and requirements

To be able to run the optimization model of this research in the case study, it was necessary first to go over the project schedule and choose a project duration and check the scheduled volumes and different parameters for the selected period so that the optimization model can give optimal solutions. After studying time schedule of this project, which was prepared in Primavera V.6 format, the month of April in 2016 was selected. Based on the project calendar, there are six working days each week. Therefore, the total number of working days in selected duration was ten days for this analysis. The main scheduled activities in the selected period were excavation and earthmoving. Also, scheduled duration of each activity along with their estimated budget was extracted from resource loading page of the project schedule. The expected result for this case study after running the model, was a proposed selection of equipment to meet the scheduled volumes of each activity in scheduled durations and under estimated budget. These results were expected while minimizing the total cost of equipment and also producing emission. Respective volumes, estimated budgets, and scheduled durations of each activity are presented in Table 3. This information was required to be given to the model as input for the working days in chosen duration (w), set of project activities in chosen duration (A), schedule duration of each activity (D), estimated budget for each activity (B), and volumes of activities (V), which were described earlier and cited in the of mathematical model. The data that was given to the model as input is described in the next section of this section.

Table 3 Case study activity types and specifications

Activity type	Unit	Quantity	Estimated budget ($)	Scheduled duration (days)
Excavation	CY	17,955	19,335	10
Earthmoving	CY	10,368	18,884	6

Note: CY, cubic yard.

4.2 Considered input for model

A part of the information, required to be collected for the case study, was production rates of the project contractor for each activity as well as productivity factor. After a series of meetings with the executives of this project and also company's western office, the company provided a very informative document regarding their production rates for different activities in California. The production rates for the mentioned activities of this case study are presented in Table 4. In addition, it is important to calculate the productivity factor of construction equipment based on project conditions. After visiting the project site and also meeting the project executives, superintendents, and project engineers, the contractor shared information about project conditions from the perspective of weather, equipment trafficking, and geographical location. Due to the educational environment of constructing this project, the employer has enforced some limitations for the number and time of project equipment to maintain students' safety and also the level of project noise. Therefore, the productivity factor of this case study was considered as 0.9. Also, the limit of maximum number of active equipment on the site was 15.

Table 4 Production rates for case study activities

Activity type	Unit	Daily production rate of contractor
Excavation	CY/Day	2000
Earthmoving	CY/Day	2000

Note: CY, cubic yard.

The next integral set of input data, which needs to be given to the model, was the project fleet. All different types of equipment with their technical parameters, emission, cost, and productivity characteristics need to be collected and entered into the model so that the optimization model can make the optimal selection among them. The available equipment for this project work is presented in Table 5.

In this case study, it is assumed that two different types of articulated haulers can be applied to the earthmoving activity and two different types of dozers can be applied to the excavation activity (Table 6).

Table 7 and Table 8 show the costs and SIs which were automatically returned to the Sustainability Matrix for the equipment considered in this case study.

4.3 Results and outcomes of optimization model

The optimization model produced the optimal solution after 26 iterations. The optimization process was conducted by the software Gurobi ver. 6.5.1 after the mathematical model was programmed in the software MATLAB R2016a. The result shows that the optimization model has selected one piece of equipment from Tier 1, 3 pieces of equipment from Tier 2, and only 1 piece of equipment from Tier 3. The outcome of the optimization model indicates that the budgetary limitation, resource availability, and volume expectations are all met. Also, the cost and emission have been minimized, while the required average for SI of the whole equipment has been met. With the information provided to the model and with consideration of assumptions that there are only 3 pieces of available equipment from each type, the following solution is reported in Table 9.

Table 5 Case study available equipment

Equipment				Technical spec.	Daily capacity				
Category	Model	ID	ID#	Engine power (gross HP)	Unit	Tier 0	Tier 1	Tier 2	Tier 3
Articulated hauler	Volvo A35D	ArtA35D	1	393	CY/Day	624	624	624	624
Articulated hauler	CAT T730	ArtT730	2	375	CY/Day	528	528	528	528
Dozer	John Deere 550J	Doz550J	3	85	CY/Day	436	436	436	436
Dozer	John Deere 750J	Doz750J	4	145	CY/Day	761	761	761	761

Note: CY, cubic yard.

Table 6 Allowed equipment for each activity in case study

Activity type	Allowed equipment	
Excavation	John Deere 550J	Doz550J
	John Deere 750J	Doz750J
Earthmoving	Volvo A35D	ArtA35D
	CAT T730	ArtT730

5 Conclusions

Solution output of the proposed decision-support tool provides an optimal option of equipment pieces to be utilized during each period of construction projects. After the consideration of SI in the analysis, the outcome is expected to be even more insightful for decision-makers. Similarly, when combined with a web-server such as management tools, this approach can benefit contractors in decision-making for purchasing, leasing or renting construction equipment for the project. The tool uses data that is practically available for construction projects of any size. In addition to the readily available data with this approach, the decision-maker may need to evaluate how much power is necessary to generate by task category. Power evaluation can be set on a regular excel spreadsheet and be used on every project by task category. The output of the method and the model can aid contractors in quantifying the sustainability level of their construction fleets. It helps understand the potential expenses needed to meet environmental standards or identify investment necessary for new equipment pieces while reducing project-based emissions. By considering equipment availability as rented or leased in the pool of possible equipment for selection, the developed model helps in decisions for augmentation of equipment fleets through renting or leasing. Cost elements included in the objective function of the mathematical formulation (WB-CEMS) can address the changes in cost as a function of the purchase price with consideration of depreciation, or terms of the lease as well as rental prices, along with tax regulations. SI may help policy developments that regulate the industry requirements.

The developed decision-support tool can help construction company owners and managers in maintaining the profitability of the business in a carbon-regulated future. This can be achieved by facilitating decisions that are aimed at meeting applicable new regulations or reducing harmful impacts on the environment by making improve-

Table 7 Daily costs of each equipment in case study

Equipment type				Cost				
Category	Model	ID	ID#	Unit	Tier 0	Tier 1	Tier 2	Tier 3
Articulated hauler	Volvo A35D	ArtA35D	1	$/Day	617	653	726	871
Articulated hauler	CAT T730	ArtT730	2	$/Day	527	558	620	744
Dozer	John Deere 550J	Doz550J	3	$/Day	399	422	469	563
Dozer	John Deere 750J	Doz750J	4	$/Day	304	322	358	430

Table 8 Sustainability Index of each equipment in the case study

Equipment type				Sustainability Index			
Category	Model	ID	ID#	Tier 0	Tier 1	Tier 2	Tier 3
Articulated hauler	Volvo A35D	ArtA35D	1	0.70	0.77	0.84	0.88
Articulated hauler	CAT T730	ArtT730	2	0.72	0.79	0.86	0.90
Dozer	John Deere 550J	Doz550J	3	0.65	0.72	0.78	0.81
Dozer	John Deere 750J	Doz750J	4	0.70	0.77	0.84	0.88

Table 9 Optimization Model results for the case study

Equipment type				Proposed number			
Category	Model	ID	ID#	Tier 0	Tier 1	Tier 2	Tier 3
Articulated hauler	Volvo A35D	ArtA35D	1	0	1	1	0
Articulated hauler	CAT T730	ArtT730	2	0	0	1	0
Dozer	John Deere 550J	Doz550J	3	0	0	0	0
Dozer	John Deere 750J	Doz750J	4	0	0	2	1

ments in their equipment fleets. This can also help a construction company in better positioning itself for government-provided incentives for environmental stewardship.

References

ARB (2007). "OFFROAD model". Off-Road Emissions Inventory. California Environmental Protection Agency. http://www.arb.ca.gov/msei/offroad/offroad.htm, 2010-4-10

ARB (2010a). "Proposed Amendments to the Regulation for in use Off-Road Diesel-Fueled Fleets and the Off-Road Large Spark-Ignition Fleet Requirements". California Environmental Protection Agency. http://www.arb.ca.gov/regact/2010/offroadlsi10/offroadisor.pdf

ARB (2010b). "Carl Moyer Memorial Air Quality Standards Attainment Program". California Environmental Protection Agency. http://www.arb.ca.gov/msprog/moyer/moyer.htm

Avetisyan H, Miller-Hooks E, Melanta S (2012). Decision models to support greenhouse gas emissions reduction from transportation construction projects. Journal of Construction Engineering and Management, 138(5): 631–641

Avetisyan H, Skibniewski M (2014). "Web–Based Management System for Construction Equipment Fleets: Global and Local Allocation of Equipment". Project Management Symposium, MD, College Park. ISSN 2374–9377, 34–43

DieselNet (2013). "Tier 1–3 Emission Standards". https://www.dieselnet.com/standards/us/nonroad.php

Environmental Protection Agency (EPA) (2009a). "Greenhouse Gas Emissions". Climate Change. http://www.epa.gov/climatechange/emissions/index.html

Environmental Protection Agency (EPA) (2009b). "EPA NONROAD Model Updates of 2008". April 2009 International Emission Inventory Conference. http://www.epa.gov/ttn/chief/conference/ei18/poster/harvey.pdf

Fan H, Abourizk S M, Kim H, Zaïane O (2008). Assessing residual value of heavy construction equipment using predictive data mining model. Journal of Computing in Civil Engineering, 22(3): 181–191

UCSUSA (2015). "California's Clean Construction Regulation". http://www.ucsusa.org/our-work/clean-vehicles/california-and-western-states/californias-clean-construction-regulation#.VOwb93zF-So