RESEARCH ARTICLE

Hakob AVETISYAN, Miroslaw SKIBNIEWSKI

Web-based construction equipment fleet management system: cost-effective global and local allocation

Abstract Over the last two decades, construction contractors have been gradually making more investments in construction equipment to meet their needs associated with increasing volumes of construction projects. At present, from an operational perspective, almost all contractors pay more attention to maintaining their equipment fleets in well-sustained workable conditions and having a high accessibility of the necessary equipment pieces. However, such an approach alone is not enough to maintain an efficient and sustainable business. In particular, for large-scale construction companies that operate in multiple sites in the U.S. or overseas, the problem extends to an optimal allocation of available equipment. Given the current state of the construction industry in the U.S., this problem can be solved by geographically locating equipment pieces and then wisely re-allocating them among projects. Identifying equipment pieces geographically is a relatively easy task. The difficulty arises when informed decision-making is required for equipment allocation among job sites. The actual allocation of equipment should be both economically feasible and technologically preferable. To help in informed decision-making, an optimization model is developed as a mixed integer program. This model is formed based on a previously successfully developed decision-support model for construction equipment selection. The proposed model incorporates logical strategies of supply chain management to optimally select construction equipment for any construction site while taking into account the costs, availability, and transportation-related issues as constraints. The model benefits those responsible for informed decision-making for construction equipment selection and allocation. It also benefits the owners of construction companies, owing to its cost-minimization objective.

Keywords Construction equipment, Equipment assignment optimization, Web-based asset management

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

Miroslaw SKIBNIEWSKI
Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20742, USA

1 Introduction

Construction equipment allocation has been an important and complex problem ever since the early application of construction equipment in construction sites. Growing industry needs, scarce resources, and environmental restrictions, along with the consequences of non-optimal industrial operation make this problem even more alarming and urgent. During the economic downturn, the growth of the industry moderately slowed down. The economy is recovering from the recession not only in North America and the U.S. in particular, but also in other continents of the world (Hon, 2014).

To track the industry performance, the American Institute of Architects (AIA) compiles data semiannually from popular national construction forecasting agencies, which allows the development of its consensus. Based on these surveys, the forecasters already noticed the decreasing rate of the construction industry recovery for 2013. Based on the 2013 midyear update for the 2014 outlook update, the AIA indicated a growth rate of 7.6%. If we discard the impact of the economic shocks on the construction industry, it can be surely stated that the size of the industry is gradually growing. In this regard, during the last two decades, the investments from large contractors in construction equipment have been increasing. The fact that investments were increasing to satisfy the industry needs related to growing construction volumes was also stated by Stewart (2000). According to the Association of

Equipment Manufacturers (AEM), in 2004, worldwide construction equipment sales increased by 8.8%, which was estimated to be 7.0% at the end of 2005 (AEM, 2004).

However, the increase in the industry is not uniform. Wells Fargo conducted an economic evaluation for equipment financing of its clients and indicated such results in the report (Crum, 2013). The studies were carried out based on surveys of construction industry representatives (347 executives) ranging from large to small firms, and revealed that non-residential construction was expected to grow in 2013 compared to 2012. As a result of the survey, it was concluded that the industry was moving ahead. Similarly, the industry expects the rental rates of construction equipment to increase. The survey results also indicated that the residential construction sector has a potential for leading the current state of the industry and that the contractors will buy new and pre-owned construction equipment. As such, the survey results are presented for three consecutive years and prove to be interesting but at the same time, they are also predictable. Almost one third (28.9%) of the respondents have estimated the timeline for non-residential sector recovery by the third quarter of 2014 or beyond. Similarly, more than one third (33.5%) of the respondents expect residential volumes to increase within the same timeframe.

Another method of evaluating the increasing trend in equipment utilization is the observation of market behavior. The survey by Wells Fargo provided useful information about the contractor preferences for working with one to five dealers for construction equipment. During the year 2011 almost 30.7% of contractors worked with three dealers, while 38.7% worked with five dealers. These proportions changed in 2013, when 37.7% still worked with five dealers and 24.6% worked with three dealers. The decrease in the percentage of contractors working with three dealers is mostly due to those switching to four dealers. These dynamics indicate that contractors are looking for more options and offers. Certainly, their goal is to increase potential profits or minimize the expected costs. When the respondents answered the question of what the dealers could do to improve the business, 47% replied that they should reduce the prices. This value represents an increase of 11% from the 2012 results (36%) (Crum, 2013).

As a result of common practice and tested methods, construction contractors and dealers focus more on maintaining their equipment fleets in a well-sustained and workable condition, while emphasizing the importance of equipment availability. In fact, in current practice, equipment monitoring is automated. Equipment management processes have been simplified by ongoing modernization in many construction equipment types based on artificial intelligence and automation techniques pertaining to equipment-related Information Management Systems (IMS). Data related to the status and operations of construction equipment can be automated and collected through onboard computer control systems. Collected data can then be accessed or transmitted, stored or reported electronically in a very short time using equipment Information Management Systems (IMS) and wireless communications.

Despite the improvement of data collection processes, the equipment management efficiency for a medium-to-large contractor or equipment distributor may not necessarily increase proportionally. Large datasets on fleet maintenance, repair, and operation prevent the company equipment manager from converting these into functional formats. Surveys of contractors conducted by Fan et al. (2008) stated that approximately 10%–20% of collected data is utilized in the process of decision-making. For any contractor managing large construction equipment fleets, it is important to identify all problems, both at the operational and corporate levels. In most cases, without even taking into account the possibility of improving the system, the company equipment manager is likely to concentrate on issues only if there is something wrong (Fan et al., 2008). As a consequence, the contractors face higher and continuously growing costs and inefficiencies.

In this paper, it is suggested that contractors using their own fleets or using equipment from a third party on more than one construction site will benefit if they allocate construction equipment in construction sites dynamically, meaning that they actively reallocate or redistribute construction equipment over time, subject to technical and/or regulatory conditions.

For better results, it is also suggested to use recorded data to track the level of work completed by the equipment, which will allow one to measure or estimate the completion time or percentage of work done by referring it to a baseline schedule or percent completion. This approach enables estimation of when the equipment piece will become available. The proposed system consists of an online web-based framework where with the help of tracking devices, the data is collected and transmitted to a central model. The collected data are then filtered and tracked in the central model and become input for the decision-making model.

Some variations for data collection systems have already been developed and are commercially available. However, the purpose of such systems is different and managers use them for tracking the fuel usage, idling, speeding, and mechanical conditions of vehicles. Some of these systems are still in the development stage and require further improvement before being able to provide sufficient and accurate data.

The method developed in this research suggests the use of a much simpler mechanism for tracking the equipment and collecting relevant data for optimal allocation of equipment in construction sites. A more sophisticated approach is also suggested for using sensors that can track the percentage of work completion, but such effort will require further analysis. In the suggested method, it is

recommended to employ existing tracking systems and use part of the resulting data in the decision-making process for equipment allocation.

2   Construction equipment tracking tools

To manage equipment fleets, many researchers have tried to develop accurate and reliable techniques. As stated previously, most of the fleet management tools available on the market are specialized for maintenance issues, that is, for equipment pieces to be available when they are needed. In fact, the real-time tracking of equipment is also very important in order to better allocate existing equipment pieces. The location of equipment can be tracked with existing tools available in the market. One of the fleet management software applications in the market is "FleetFocus", capable of managing diverse fleets of all sizes. This software application is capable of tracking all functions associated with the maintenance of equipment and vehicles, such as preventive maintenance, work orders, processing repairs, analyzing operational expenses, computing billing, and recording the usage of vehicle equipment. Besides including the standard features, Fleet-Focus works in real-time using a single dataset (Asset-Works, 2009).

There is also another software package called Mobile-Focus, which works with FleetFocus to help technicians and inspectors access the system regardless of their location. In particular, it has full work order functionality, reports defects in real-time, reviews previously recorded defects, tracks work-related and inspection-related activities of labor in real-time, analyzes the history of maintenance and inspection for all assets, provides entry of diagnostic test outcome, provides entry of fuel tickets and entry of meter readings and in addition, it can provide functionality of robust parts inventory. Using a wireless network or a batch mode upon return to the maintenance facility, the technician can upload the data recorded on the MobileFocus device to the AssetWorks database (Asset-Works, 2009).

One of the key factors for having sustainable practice is to consider the emissions generated from construction equipment. Emissions should be considered in the decision-making process for fleet management. In particular, if a certain level of emissions needs to be complied with at a given construction site, the decision-maker may decide to trade-off among the productivity, cost, and schedule. MobileFocus and other software package provide an emissions-tracking option that is in most cases based on the fuel consumption rates. Emissions tracking is also available through "OnTrack-GPS Fleet Management" (Telogis, 2009), which uses GPS technology for collecting and transmitting data about the vehicle. "OnTrack-GPS Fleet Management" offers GPS tracking, navigation and routing of vehicle, reporting related to

maintenance, satellite-technology-based imagery, as well as a module for fuel efficiency. Managers can quickly find critical data for any fleet size through a screen which displays crucial KPIs, allowing managers to observe important fleet-related parameters (fuel efficiency, arrivals, idling time, speeding, maintenance alerts, etc.). There are also other packages available on the market that contractors use for fleet management. Such packages, that already employ web-communication, can provide the necessary information for the web-based construction equipment system (WB-CEMS) developed in this study.

3   Sustainability factors

For sustainable business, any factors that can affect decision-making should be considered. One of the commonly used measures is greenhouse gas (GHG) emission levels. The construction sector in the U.S. plays a significant role in the addition of GHG emissions into the environment. Based on the data provided by the U.S. Environmental Protection Agency (EPA), approximately 1.7% of U.S. GHG emissions (as of 2003), or approximately 6% of the total industrial GHG emissions in the U.S. come from construction industry, which places the industry in the list of primary emitters (EPA, 2009). This should not be confused with project-by-project emission quantities that may not produce large amounts of GHG emissions when compared to specific operations in other industries, but it should be considered on a larger scale. There are many ongoing construction projects and the aggregate product of these projects is what causes the global effect of the industry on the amount of emissions. Overall, the U.S. generated 5839.3 million metric tons (MTs) of carbon dioxide in 2008 derived from fossil fuel usage (Environmental Protection Agency, 2009). It can be noticed that the construction sector alone generated approximately 100 million MTs of carbon dioxide just in 2008. Based on these facts, the construction sector in the economy is considered to be the third largest GHG emitter (Truitt, 2009). Similarly, the construction sector ranks third for its carbon dioxide emissions per unit of energy input. It is noteworthy that the cement and steel industries are the first and second in the ranking (Amano and Ebihara, 2005), yet these sectors supply necessary materials for construction projects.

The contributions of the construction sector to GHG emissions into the atmosphere is mostly due to the dependence of construction equipment on fossil fuels as an energy source for their operation. Given the continuous demand and dependence for fossil fuels, an increase in GHG emission levels is analyzed by the U.S. EPA studies (EPA, 2009). Construction equipment are mainly non-road vehicles, which on average, generate a much greater amount of emissions in comparison to passenger vehicles (see Report MS-12, 1997 for more detail). Such a

difference in emission quantities is also due to the fuel type used. Construction equipment is mainly fueled with diesel, with different engine technologies, and much higher horsepower. For example, one can estimate that a typical excavator produces 454 pounds of carbon dioxide per hour of operation, while a typical medium-size passenger vehicle (or sports utility vehicle) produces 55 (or 78.5) pounds of carbon dioxide per hour of operation.

Over time, national and international support for reducing the overall carbon footprint in the environment is growing, and therefore, in the proposed model, emission-related costs are included as a key basis for decision-making. Construction equipment manufacturers continuously work to improve their engine technologies and as a result, many companies have switched to low-sulphur diesel, which has enabled significant reductions in the level of sulphur-oxide emissions (considered as a GHG). In many cases, construction projects provide flexibility when it comes to the choice of equipment for a given task on a construction job. Such flexibility may possibly reduce costs and emissions resulting from individual construction jobs through informed assignment of construction equipment pieces for specific jobs from the available pool of construction equipment (Avetisyan et al., 2012).

4   Proposed methodology

Agencies, such as state departments of transportation (DOTs), have many large and ongoing construction projects. Competing contractors try to get the projects based on more accurate estimates of cost and duration, as well as their reputations. When it comes to cost efficiency, the high cost of new and more efficient construction equipment becomes less favorable when compared to older and more emissive equipment pieces. To make sure that for the environmental aspects are considered in decision-making for construction equipment selection, it is often

required that the selected equipment mix for new projects meet EPA Non-road Diesel Tier System requirements. These requirements limit the proportion of such older and less efficient equipment on a job site.

In this paper, an optimization-based methodology is developed and proposed for building a web-based construction equipment management system based on previous work by Avetisyan et al. (2012) to aid a construction firm in profitable decision-making for construction equipment selection and usage while satisfying technical, emissions cap, and budgetary requirements. Load factor, engine power, fuel consumption rates, and technological differences between equipment of different manufacturers, as well as other equipment characteristics, can be explicitly considered. The developed tool is generic and can be used for any construction site with varying site elevations, geographic specifics, soil properties, and any other factors that may potentially affect equipment productivity and operation.

A schematic representation of the proposed web-based system is presented in Fig. 1. The top level in Fig. 1 is the decision-making unit that analysis and optimizes the selection and allocation of construction equipment among construction sites. The lower level represents construction sites, where the data collecting systems are installed for transmitting data to the top level and collecting results for optimal site operation. The arrow in the third level of Fig. 1 indicates that the information exchange is not solely between the centralized decision-making system and the construction sites, but also among the construction sites controlled by the single company.

Figure 1 accurately depicts the structure of the proposed web-based construction equipment management system, where the top level unit is responsible for all decision-making and problem-solution activities, while the lower levels are responsible for data transmission and implementation.

To have the lower level of the WB-CEMS installed in construction sites, the contractor needs to have either one
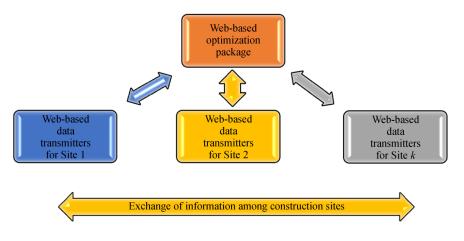
Fig. 1   Schematic representation of web-based construction equipment management system

of the software packages for maintenance or install a GPS tracking system for the simplified option. From the software, the user will need to extract data regarding the ID of a given equipment piece, its location, and duration of application on the construction site and transmit that information to the central system. The top-level part of the system will analyze the provided information and will send back results that will include data regarding the optimal combination of construction equipment to be used in each construction site.

Limited details of the system formulation as an optimization model are provided in the next section, followed by preliminary results from variation of input data of a real case study and its hypothetical modifications. In particular, for the purposes of a case study to analyze the effectiveness of the optimization model, the actual project values had been modified by certain proportions to imitate another project that a contractor may have in hand for completion.

5 Mathematical model and solution

In this research, a multi-period, triple-objective, linear, integer program is developed for the WB-CEMS. The primary objective of the developed model is to allow selection of construction equipment from a list of available construction equipment. For each stage of a construction project, there are many simultaneously progressing activities subject to many constraints to meet work, regulatory, or temporal requirements, which negatively impact the total cost of construction equipment from ownership and operation, rental, lease or purchase, transportation, and emissions abatement over the project's duration. The construction period in the model is presented at a set S of discrete time intervals $t = \{t_0 + n\Delta\}$, where $n = 0, 1, 2, …, I$. In such a setup Δ represents any increment of time, e.g. one minute, hour, day, week, or even longer. It should be noted that the number of selected pieces of construction equipment should be for the amount of work to be completed in given time period t at construction site k. To make sure that there is no confusion between construction sites, an origin and destination (OD) approach is applied. This means that the move of construction equipment from one site to another will be defined with two indices, j and k.

Many states in the U.S. request construction contractors hired for state construction jobs to comply with the U.S. EPA's Non-road Diesel Engine Tier System requirements. Mapping of a tier category to a particular construction equipment piece is subject to a year of manufacture, fuel type, efficiency of the engine, and whether the equipment has been retrofitted for the purposes of reducing its emission levels. Many federal projects suggest certain guidelines for construction equipment fleets, based on the EPA Tier System classification, which encourage reduced emissions resulting from construction equipment utilization. For example, Maryland's requirements associated with the Inter County Connector highway project construction equipment mix are presented in terms of percentages for construction equipment on the site at any time during the construction. These particular percentage requirements are provided in Table 1, where the highest tier, Tier 3 (Tier 4 is mostly constraining NO_x emissions, and therefore not specifically considered), includes the least GHG emissive equipment. The Tier System requirements presented in Table 1 are considered in the proposed model, which can be modified as necessary (Avetisyan et al., 2012).

Table 1 Maryland's tier system guidelines for construction equipment on project sites

EPA Tier	Equipment limitations by percentage on site
Tier 0	Must not exceed 10%
Tier 1	Must not exceed 70% (combined with Tier 0)
Tier 2	Must not exceed 90% (combined with Tiers 0 and 1)
Tier 3	Must be no less than 10%

1. 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 construction equipment tier levels

Y = set of construction equipment types (e.g. trucks, excavators, cranes, loaders, etc.)

c_{xyjk} = cost of operating or renting, leasing or owning each type of equipment $y \in Y$ in tier $x \in X$, at site jk, $j \in J$, $k \in K$

cm_{xyjk} = cost of moving or renting, leasing or owning each type of 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

w_{jkt} = number of working days at site jk, $j \in J$, $k \in K$, in period $t \in S$

β_{jkt} = discounting factor for inflation at site jk, $j \in J$, $k \in K$, by period $t \in S$

2. Decision variables

α_{xyjkt} = number of construction equipment of type y, $y \in Y$, in tier x, $x \in X$, at site jk, $j \in J$, $k \in K$, to be utilized during period $t \in S$

3. Formulation WB-CEMS

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

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

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

$$Z_2 = \text{Min} \sum_{t \in S} \left[\sum_{x \in X} \sum_{y \in Y} \sum_{j \in J} \sum_{k \in K} w_{jkt} \cdot g_{xyjk} \cdot \alpha_{xyjkt} \right], \quad (1b)$$

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

The set of constraints is not presented in this paper, but is conceptually discussed in the following paragraphs. The first objective (1a), allows the selection of equipment while minimizing the total cost related to completion of construction tasks for the construction projects under consideration. The second objective (1b), minimizes emissions measured in carbon dioxide equivalents produced from the construction activities from all construction sites under consideration. The third objective (1c) minimizes the costs of moving construction equipment from one site to another. The constraints of the model are arranged according to three general categories: constraints that consider construction activity requirements, constraints that consider emissions limitations, and constraints that consider budgetary caps relevant to the equipment mobilization, operation and/or ownership costs.

From the perspective of practical application of the model, it is considered that equipment availability is enforced either through Construction Company's fleet or through any local rental or leasing shop. Similarly, workload parameters are formulated and included along equipment pairing requirements. Workload parameters can be easily understood if one considers the specific task, such as cut-and-fill activity, which in most cases requires soil compaction. Therefore, the construction equipment assigned to complete such work must be selected so that the capacity of the construction equipment exceeds the amount of work associated with the compaction work for the given time period. The time limitation for completion of activities is also formulated by considering that each piece of construction equipment has a specific productivity rate that is a function of the equipment's horsepower and many other technical characteristics, including conditions associated with the construction site. These include but are not limited to soil type, elevation, and weather. The pairing of equipment can be illustrated by considering, for example, the work of two equipment such as a loader and a truck. The difference in capacities of this type of equipment operating together needs to be controlled. The total quantity of construction equipment pieces in the site must be restricted at any time period. This limitation is also included in the mathematical formulation.

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6 Practical application and preliminary results

6.1 Case study design

The developed mathematical model was used to evaluate an actual project consisting of a 7.2-mile section (known as Contract A) of a much longer roadway of 18 miles named the Inter County Connector or ICC (Avetisyan et al., 2012). The case study demonstrated the application of the developed model and its potential benefits for decision-makers. Due to the lack of data and information availability even for an existing project, many calculations and assumptions were made to complete the required input dataset. As a base scenario, a real project is applied for one of the sites and the other site is generated based on the actual data by changing required work volumes and durations. Such an approach was based on engineering judgment and guaranties approximately reasonable parameters of hypothetical site/s.

Some estimations were used as in Avetisyan et al. (2012) for equipment cycle times. The cycle times consequently define the work amount each construction equipment piece could complete during given day. For these calculations, 75% "duty days" and eight-hour workdays were assumed. The work amount that was scheduled for completion in each work category was estimated from contractor-provided total work estimates. To do so, prior knowledge of construction processes along with categories of construction equipment assigned to each task as well as the productivity rate estimates were considered. The productivity rate for each construction equipment piece also depends on the cycle time. Cycle time is a function of equipment piece speed and the operation it must perform and/or distance over which the machine should travel. Cycle times for construction equipment depend on many factors, including soil properties, water content in the soil, and geographic location, which defines the terrain and the underfoot. Part of the data and information provided by the contractor did not consider every specific detail of the project and therefore, estimates were made. Moreover, for

comparison purposes, it was assumed that the list of construction equipment utilized for ICC project contract A is available in for every tier level. For the construction equipment cost, data related to ownership and operating expenses information from the U.S. Army Corps of Engineers for Region II (Hill, 2009) was considered.

The market price for CO_2e (i.e. carbon credit) adopted in the study considered the carbon price on the market as reported by the Chicago Climate Exchange, which represents the best structured carbon markets in the U.S. at the time of the construction period of ICC project. Since the carbon market is voluntary in the U.S., the price of one ton of CO_2e in the market reflects the amount that any company would be willing to pay. For the sake of comparison, three different values for CO_2e price per ton were analyzed: \$5/MT, \$30/MT, and \$50/MT. The upper range cap value of \$50/MT is included in the analysis, owing to the estimates done by economists as an amount that is required to pay in order to reach 65% emission reductions by 2030 in all developing countries (World Bank, 2010).

6.2   Case study results and analysis

The results indicate that noticeable emission and cost reductions (approximately 30%) are achievable, owing to informed choices for construction equipment made by the decision-maker.

7   Conclusions

The results obtained from the developed mathematical model provide optimal selection options for construction equipment that can be utilized for any period of time during any construction project. In combination with a web server, this managerial decision-support tool can help contractors in making decisions for buying, leasing, or renting construction equipment for their business. The developed tool relies on data that is available for any construction project. The output of the model can assist contractors in finding suitable options for lowering costs and meeting environmental standards Moreover, the tool aids in decision-making for renting or leasing construction equipment if they can be included in the pool of available pieces of equipment for any project under consideration. The cost terms included in the objective function of the model formulation (WB-CEMS) account for changes in costs as a function of purchase price, depreciation, salvage value, terms of lease or rental prices, as well as tax regulations.

Owing to unforeseeable circumstances, such as inclement weather, tasks in construction projects may be delayed, which may adversely affect project completion time. The developed model also aids in such delay

circumstances, as it provides optimal equipment selection for future time periods and can reduce the impact of the delays through re-allocation of construction equipment pieces among all construction sites operated by the same contractor. The feasibility, as well as the cost of reducing the duration of projects to obtain a bonus for early completion can be analyzed through the model as well.

The developed methodology can help construction companies in sustaining profitability in a carbon-regulated market by facilitating decisions directed at meeting new emission regulations or reducing environmental impacts by applying changes to its construction equipment fleet. Use of the model can also help contractors achieve better positioning in the market to receive government-supported incentives for environmental stewardship.

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