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An Economical Operation Analysis Optimization Model for Heavy Equipment Selection

A. Jrade, N. Markiz, and N. Albelwi

Abstract**—**Optimizing equipment selection in heavy earthwork operations is a critical key in the success of any construction project. The objective of this research incentive was geared towards developing a computer model to assist contractors and construction managers in estimating the cost of heavy earthwork operations. Economical operation analysis was conducted for an equipment fleet taking into consideration the owning and operating costs involved in earthwork operations. The model is being developed in a Microsoft environment and is capable of being integrated with other estimating and optimization models. In this study, Caterpillar® Performance Handbook [5] was the main resource used to obtain specifications of selected equipment. The implementation of the model shall give optimum selection of equipment fleet not only based on cost effectiveness but also in terms of versatility. To validate the model, a case study of an actual dam construction project was selected to quantify its degree of accuracy.

Keywords**—**Operation analysis, optimization model, equipment economics, equipment selection.

I. Introduction

EQUIPMENT selection is a critical factor in the execution of many construction projects. This is to be much more critical in heavy construction projects where the equipment fleet plays a vital role in performing the work. In this type of projects, the equipment fleet may represent the largest portion of the bidding price [12]. Consequently, successful contractors and construction managers understand the substantial impacts on their projects when equipment management decisions are not made in a proper and timely manner. Since equipment selection is highly influenced by myriad factors, most contractors tend to rely upon their historical data and experience in similar projects to assist them in determining the optimum fleet. While this is a good approach at the conceptual stages of the project, it is not sufficient to build the equipment fleet benchmark due to the dynamic nature of construction projects. Other approaches such as expert systems could be useful if only integrated with a database of historical data. To overcome this shortcoming, the proposed model is being developed based on integrating manufacture's data for selected pieces of equipment with a comprehensive economical operation analysis for different scopes of earthwork operations.

At this stage, however, the developed model includes an optimization of equipment fleet based on simple economical operation analysis.

II. Literature Review

Presently, the majority of the studies published in the literature focus on the optimization of equipment selection in heavy civil work based on diverse complex factors; however, none of the studies were to include or perform economical operation analysis. One study conducted by [11] addressed cost estimation of heavy earthmoving operations. In their study, an equipment cost application system for time and cost estimation of heavy earthmoving operations was developed. The developed system was then verified by a numerical example with a detailed step-by-step description of the procedure to be followed. This study is of major significance at the conceptual stage of a construction project and is limited to initial costs anticipated for earthmoving operations. Another study conducted by [9] addressed cost applications without considering complex factors in heavy equipment operational analyses. In their paper, an object-oriented simulation model for earthmoving operations (SimEarth) was developed. The model was implemented in a Microsoft environment to enhance its components integration capabilities with the Visual Basic® 6.0 code. The proposed system consisted of the simulation program, a database and cost applications, and optimization and reporting module. The main focus of their paper, however, was targeted towards the earthmoving simulation program (EMSP) only. At the end, the study was verified with a numerical example by comparing the corresponding outputs of the Caterpillar's software, fleet production and cost analysis (FPS), to the developed EMSP. It was concluded that results were in good agreement with a percentage difference less than 8%. Also, it was found that EMSP is considered more accountable than FPS for uncertainties that arise during the execution of earthmoving operations. Different methods and models have been proposed to optimize equipment selection for different types of activities. These models are proposed for specific types of construction work due to the many factors that contribute to equipment selection. Furthermore, researchers have focused on developing an expert system in an attempt to assist construction managers in equipment fleet selection. Their studies, however, did not incorporate equipments operation analysis and its associated costs. Reference [1] developed an expert system model for the selection equipment fleet in road construction earthmoving operations. This model recalled resources from field practitioners such as planning engineers and equipment specialists. The expert system was then

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developed in four main stages. The first stage of the study was to identify tasks and job conditions. Following the identification of tasks and job conditions, equipment selection was commenced based on broad categories. After that, equipment fleet was matched with the proper category. Finally, the selection of equipment fleet was made taking into consideration the factors from earlier stages. At the end, the study was concluded by stating that the expert system was developed to minimize and possibly eliminate the deficiency of basic processes and replace it with modern consultation and advice. Reference [2] developed an expert system model for equipment selection in earthmoving operations. As part of developing the expert system, a rule-based expert system was used for selecting earthmoving equipment. The system was developed to interpret data pertaining to soil conditions, operator performance, and volume required for the earthmoving operations. Later research [8] developed a model for optimizing excavating and haulage operations and the utilization of equipment in opencast mining. Their model was based on a decision-support system, XperRule, for the selection of opencast mine equipment (XSOME). As part of developing the decision-support system, a hybrid knowledge-base system and genetic algorithms were used to design the system. Furthermore, [15] developed a model based on an analytical hierarchy process (AHP). The model was intended to provide solutions for two main issues. The first was the systemic evaluation of soft factors and the other was the weighting of soft benefits when compared to costs. Also, the developed model is capable of providing users with results to compare with different alternatives based on several criterions. At the end, the output results would be the selection of equipment based on highest score. Other studies have addressed significant factors that influence operation analysis. For example, a study conducted by [10] developed a fuzzy clustering model for estimating haulers' travel time capable of being integrated with diverse simulation and estimation models. The proposed model exploits regression analysis and subtractive clustering and was implemented by means of Visual Basic® for Applications (VBA) in a Microsoft environment. It was concluded that results obtained from the developed model were in good agreement with the results obtained from the FPC software. At the end, a practical example was illustrated to demonstrate the implementation of the estimation model. The challenge to find the best method to optimize equipment selection has inspired many researchers as discussed above. Therefore, various methods and models had been proposed. However, the majority of the studies did not consider economical operation analysis. Instead, the studies focused on developing systems, algorithms, or a framework to assist the user in the selection of equipment fleet in heavy civil operations. Moreover, most of these studies included time and cost estimation at the conceptual stage of the project; however, this study includes economical operation analysis at the conceptual stage and following the commencement of the project. Furthermore, the proposed model is being developed to incorporate owning and operating costs of selected equipment fleet configuration (i.e. hourly fuel consumption, lubricant charges, repair reserves, tire replacement, etc…).

III. Equipment Economics

For construction projects, especially the heavy civil work projects, equipment is comprehended as one major resource that project managers rely upon to perform the required work. Equipment may be owned by the company or rented for a period of time. According to [14], equipment fleet may represent the largest investment in the long term for construction companies. Economic analysis of equipment must be obtained in order to properly determine the optimum fleet. This step is considered critical in order to evaluate the rental option and to support decision-makers. The economical analysis of construction equipment is mainly focused on determining the owning and operating costs as well as the economical life for each type of equipment [12]. In order to properly complete the equipment economical analysis, all costs associated with the selected equipment must be considered. In this study, Caterpillar® Performance Handbook [5] is being used to obtain data pertaining to owning and operating costs.

IV. Equipment Selection

Equipment selection is a critical factor in construction projects. Rational selection of equipment leads to profits for contractors. At the same time, miscalculating the proper size and number of fleet required for the project may result in losing the contract or suffering from overhead costs [17]. Therefore, contractors consider selection of equipment fleet a vital factor for any construction project to be successful [10].

V. Factors Affecting Equipment Selection

The main consideration in any endeavor is to get the job done according to timeframe and cost limitations. In order to achieve this goal, proper calculation of productivity rates for the fleets while considering variable factors is required. According to [7], the first factor to consider would be matching the right equipment to the proper type of activity. Another factor would be the availability of the right equipment with proper service, maintenance, and repair reserves. Besides previous factors, [7] proposed two factors that can be considered when selecting proper equipment: (i) type and condition of the site work; which includes the distance to be traveled; and (ii) desired productivity; which is a critical factor that affects equipment selection. Furthermore, [14] stated two general factors that should be considered in the process of selection of equipment fleet: (a) cost effectiveness; which involves considering the size of equipment besides the proper type; and (b) versatility; which involves selecting equipment that can perform multiple tasks at the site work.

VI. Research Methodology

Economical operation analysis of selected types of equipment is considered essential for developing the optimization model. In this paper, the developed model allows users to attain an optimized fleet for various types of earthwork. The analysis was performed for seven major activities of earthwork. The operation analysis was carried out while taking into consideration variable factors affecting the productivity of equipment. The summarized research conceptual model is shown in Fig. 1.

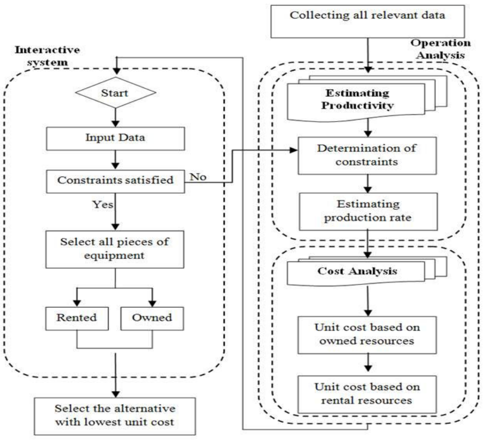


Fig. 1 Research Conceptual Model

A. Data Collection

As stated previously, equipment specifications' data needed to carry out the analysis was obtained from the Caterpillar® Performance Handbook [5]. Also, data pertaining to operation analysis was extracted and inserted into Microsoft Excel modules. These specifications' data are as follows: (i) equipment horse power; (ii) rated capacity; (iii) maximum weight; (iv) load distribution; and (v) performance charts. Some of these data had to be tabulated in order to enhance the model's capability of interfacing the data with information entered by the uses. Furthermore, it is important to note that the database of information incorporated into the excel modules possess a variety in the equipments' capacity, power, and maximum allowable weight which enables the developed model to be applied for any construction project regardless of the volume of materials involved.

B. Fundamentals of Earthmoving

The most important step in analyzing construction operations is to understand the characteristics of the materials to be moved. Soil types and properties affect the type of equipment required to successfully complete a construction project. For this study, data pertaining to material properties were obtained from the Caterpillar® Performance Handbook [5].

C. Forces Affecting Motion of Equipment

Self-propelled equipment gets the power needed from the engine. However, there are certain parameters that need to be considered when conducting the operational analysis. These parameters are: (a) total resistance force; (b) traction; (c) power; and (d) effects of altitude [6]. Prior to optimzation, all of these factors were taken into consideration while conducting the operational analysis of equipment fleet.

D. Estimating Productivity of Selected Equipment

Equipment productivity is a key factor that enables contractors to make a decision regarding the project scheduling, fleet selection, and project costs. Most contractors rely on their historical data and previous projects to obtain the productivity of selected equipment [16]. In this study, the estimation of productivity rates was performed for each type of equipment individually. Fig. 2 illustrates the detailed methodology of estimating productivity.

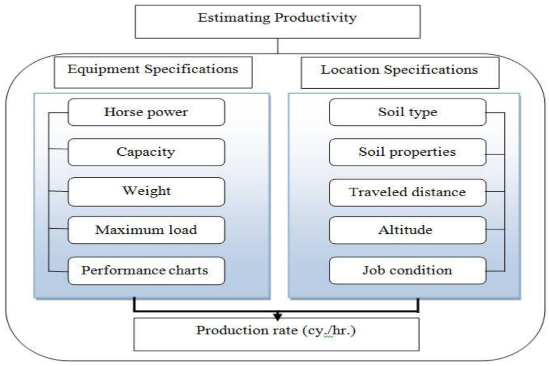


Fig. 2 Methodology of Estimating Productivity

E. Cost Analysis

Cost analysis of construction projects is a vital key for success. At this stage, simple cost analysis was conducted to illustrate the workability of the developed model. Presently, a comprehensive owning and operating cost analysis is being implemented as a stand-alone module that is capable of being linked to any optimization module. In this paper, two main equations were used to obtain costing parameters. In order to obtain the time needed to complete a certain earthwork operation, refer to (1),

$$\text{Time required (days)} = \frac{\text{Volume}}{\text{Productivity per day}} \quad (1)$$

For operating costs, Caterpillar® Performance Handbook [5] was used to obtain the operator's hourly wage. For renting costs, RS Means [13] cost estimating handbook was used. In order to estimate the unit cost for the selected equipment, refer to (2),

$$\text{Unit Cost} = \frac{\text{Total hourly cost}}{\text{Productivity per hour}} \quad (2)$$

VII. Optimization Process

Optimization is the process of maximizing or minimizing the objective function taking into consideration the prevailing constraints [4]. To optimize equipment selection, one must understand all related constraints. Failure to do so may lead to erroneous results in the final output. In this study, all constraints obtained from the operation analysis were represented in a mathematical form. Then, by using a linear programming approach, the model will select the optimum fleet that satisfies all constraints. The constraints limit the degree to which he objective function can be pursued [3].

A. Determination of the Number of Fleets Required

Each piece of equipment can perform the task within its corresponding capability and maximum productivity. However, sometimes contractors are required to achieve certain production rate to complete the job within a specific period of time. This rate is usually higher than the rate achieved by one piece of equipment. To determine the required fleet, refer to (3),

$$\text{Required fleet} = \frac{\text{Estimated completion time}}{\text{Required time}} \tag{3}$$

B. Optimization Equations and Constraints

The main objective of the optimization model is to minimize the unit cost and select the fleet that has the smallest unit cost. Operation analysis of selected pieces of equipment was carried out to determine the two main constraints that must be satisfied by each piece of equipment. The first constraint was defined as the loaded weight. The loaded weight must not exceed the maximum allowable weight set by the manufacture. To identify this constraint, refer to (4),

$$LW \leq RW \tag{4}$$

Where, LW is the loaded weight; and RW is the rated weight. The second constraint is defined as the total resistance. The total resistance must not exceed the allowable rim-pull. To identify this constraint, refer to (5),

$$TR < RP \tag{5}$$

Where, TR is the total resistance and RP is the allowable rim-pull.

If any of the abovementioned constraints was not satisfied, the model will automatically eliminate the equipment from the optimization process. All the aforementioned calculations were organized in different forms based on the equipment's type to ease the development of the model using Visual Basic® for Application. Prior to programming, Figs. 3 and 4 were established in order to identify and organize the model's components and to achieve a better understanding of the relationship that exists between the different components. This step assisted much in visualizing the entire optimization process.

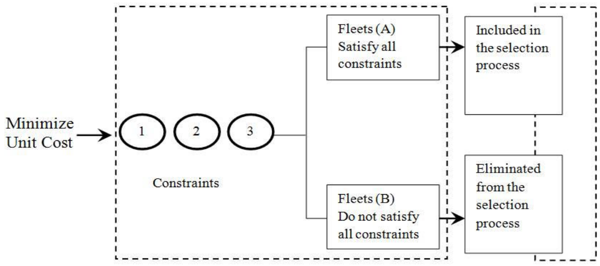


Fig. 3 Optimization Process

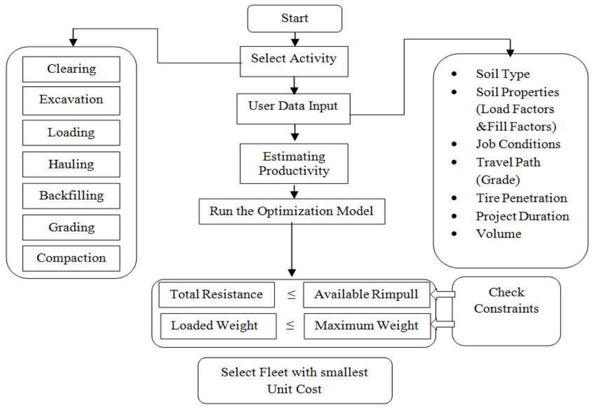


Fig. 4 Optimization Process Flowchart

Following the setup of the optimization process, a major obstacle was encountered when developing the hauling-loading system. The goal was not only to optimize the haulers selection but to also optimize the hauling-loading system as a whole. Fig. 5 illustrates the procedures used in the model to overcome the obstacle and obtain the optimum hauling-loading fleet.

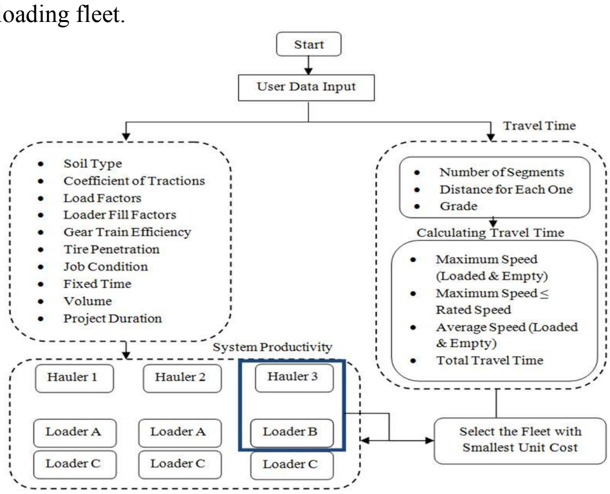


Fig. 5 Procedure of Hauling-Loading Module

VIII. Model Development

The model is developed by using Visual Basic® for Application in Microsoft Excel. The main goal is to facilitate the interface between the operation analysis, user input data, and the optimization functions. The modules were already organized by the activity names. For each activity, two more modules were created. The first module is the optimization form where optimization results will be displayed and the second module is the optimization report which contains printable tables that summarize results in the optimization form. Fig. 6 illustrates the main switchboard of the proposed model. Once the user select the desired activity, the corresponding form will be displayed. Then, the user will be required to enter the necessary data. Fig. 7 presents the hauling activity module prior to entering the data. The highlighted cells are dropdown lists. Fig. 8 shows an example of a dropdown list.

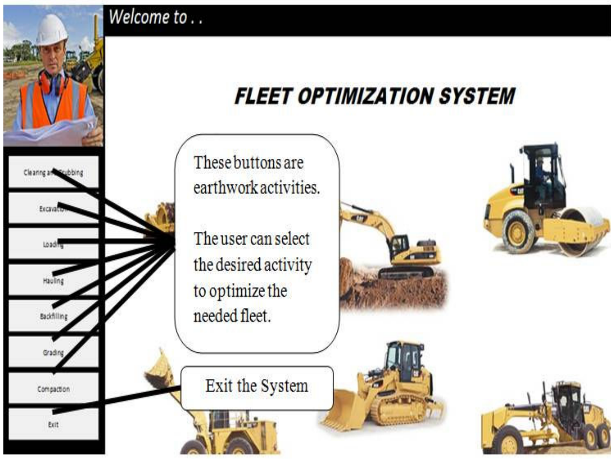


Fig. 6 Screenshot of the Model Switchboard

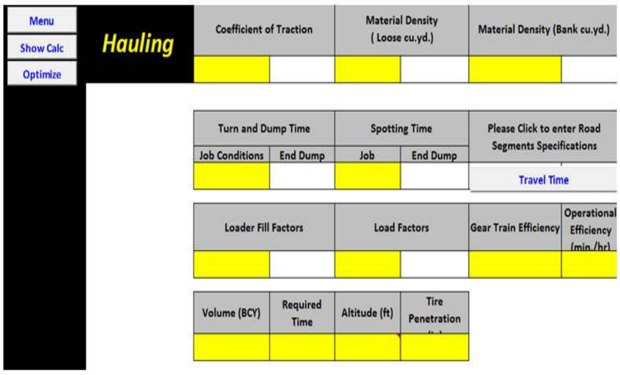


Fig. 7 Hauling Activity Module

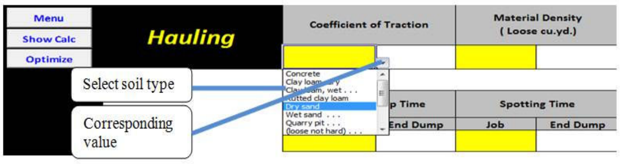


Fig. 8 Illustration of Dropdown List

Most importantly, if the constraints set by the model are not satisfied, an error message will appear to inform the user that some equipment will not be considered in the optimization process. A typical error message is shown in Fig. 9.

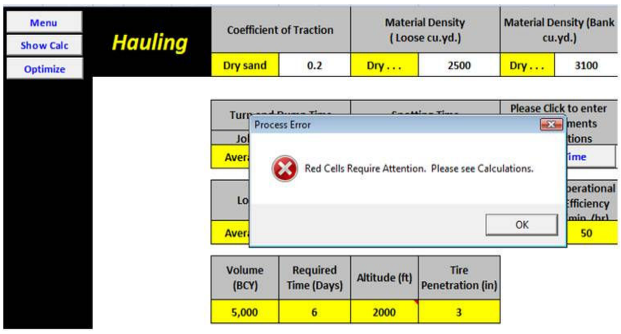
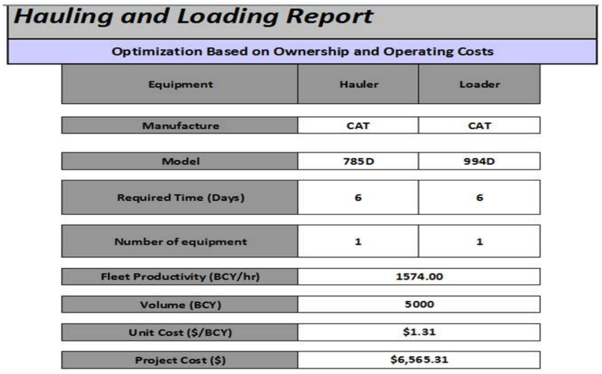


Fig. 9 Constraint Error Message

Once the user is done with reviewing operation analysis calculations, the optimization button will need to be clicked on for optimum fleet results. Fig. 10 illustrates the hauling-loading report which summarizes optimization results.



Hauling and Loading Report

Optimization Based on Ownership and Operating Costs

Equipment	Hauler	Loader
Manufacture	CAT	CAT
Model	785D	994D
Required Time (Days)	6	6
Number of equipment	1	1
Fleet Productivity (BCY/hr)	1574.00	
Volume (BCY)	5000	
Unit Cost ($/BCY)	$1.31	
Project Cost ($)	$6,565.31	

Fig. 10 Hauling and Loading Optimization Report

IX. Model Validation

To validate the model, an actual construction project was selected. The project data were obtained from an earlier published paper by [10]. The case project considers the construction of a dam built in the province of Quebec, Canada. The dam is considered as one of the highest rock fill dam in North America. Table 1 summarizes the scope of earthwork in terms of soil type and material volume. The challenge was to select the optimum fleet of equipment necessary to execute the construction. The developed model was capable of selecting the optimum hauling-loading system.

TABLE I
Scope of Earthwork Fill (BCY)

Soil Type	Stage 1	Stage 2	Stage 3	Total
Moraine	38,192	727,029	353,017	1,118,302
Granular	18,965	374,729	181,806	575,500
Rock	257,929	4,197,751	2,096,521	6,546,315
Total	309,201	5,299,572	2,631,344	8,240,117

X. Comparison Of Results

Prior to comparing results, one needs to understand the differences between the two results in order to understand the model limitations. The obtained results were compared to the actual project data and were found in good agreement with a percentage difference ranging between 4% - 32%. It should be noted that the model eliminated the 777D hauler from the optimization process because the loaded weight exceeded the maximum weight. This could be avoided if the truck is not fully loaded. However, in the model, all the haulers are assumed to perform at their maximum capacity. Comparison of results is illustrated in Tables II and III below.

TABLE II
FLEET COMPARISON

	Soil Type	Hauler Model	Loader Model	Stage 1	Stage 2	Stage 3
Model Data	Moraine	785D	992G	(3,1)[a]	(13,1)[a]	(5,1)[a]
	Granular	785D	992G	(3,1)[a]	(10,1)[a]	(5,1)[a]
	Rock	785D	992G	(3,1)[a]	(21,3)[a]	(14,2)[a]
Actual Data	Moraine	777D	992G	(3,1)[a]	(12,2)[a]	(5,1)[a]
	Granular	777D	992G	(3,1)[a]	(8,1)[a]	(4,1)[a]
	Rock	777D	992G	(4,1)[a]	(35,5)[a]	(20,3)[a]

[a](N1, N2); N1: No. of haulers and N2: No. of loaders.

TABLE III
COST COMPARISON (US$)

	Soil Type	Stage 1	Stage 2	Stage 3
Model Data	Moraine	$ 162,387	$ 3,091,465	$ 1,500,965
	Granular	$ 100,050	$ 1,970,803	$ 973,800
	Rock	$ 398,619	$ 10,096,619	$ 4,494,613
Actual Data	Moraine	$ 169,161	$ 2,696,893	$ 1,360,500
	Granular	$ 94,394	$ 1,491,515	$ 828,531
	Rock	$ 518,693	$ 13,442,660	$ 6,448,251

XI. SUMMARY AND CONCLUSIONS

When comparing results related to the rock material, it is clear that the developed model has limitations when applied to earthwork operations involving rock material. However, economical optimization of equipment fleet operating on diverse types of soils proved the workability of the model. Moreover, multiple assumptions made in this case study had significant impacts on model results. For example, tire penetration was assumed to be 3 inches. If this value was to change, the optimum fleet would be instantly affected. Also, the productivity was estimated based on an off-site methodology. For more accurate results, the data should always be obtained from the actual site and historical data. The overall results showed that the accuracy of the model varies depending on the soil type, tire penetration, altitude, travel time, and project duration. Also, model results may be improved by implementing a comprehensive owning and operating costs module. The results of this study are anticipated to be of major significance to owners, general contractors, and construction managers. Also, the proposed model would contribute to the database of fleet management systems by including a computer-coded model that integrates heavy equipment operational analysis with its corresponding economical analysis.

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