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Optimization of Earthwork Operation for Energy-saving using Discrete Event Simulation

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***Abstract**: considerate operation is a major issue in the equipment-intensive operation. Identifying an optimal equipment combination is important to achieve low-energy operations. An Earthwork operation planning system, which measures the energy consumption of construction operations by taking into account construction equipments' engineering attributes (e.g., weight, capacity, energy consumption rate, etc.) and operation conditions (e.g., road condition, attributes of materials to be moved, geometric information, etc.), is essential to achieve the low-energy consumption. This study develops an automated computerized system which identifies an optimal earthmoving equipment fleet minimizing the energy consumption. The system imports a standard template of earthmoving operation model and compares numerous scenarios using alternative equipment allocation plans. It finds the fleet that minimizes the energy consumption by enumerating all cases using sensitivity analysis. A case study is presented to verify the validity of the system.*

Keywords: Construction Equipment, Energy Consumption, Sensitivity Analysis, Earthmoving Operation, Optimization

I. INTRODUCTION

A. Research Background

Significant reduction of energy use would be achieved by saving fuel consumption of construction equipment (Guggemos and Hoarvath 2006, EPA 2009). Earthwork is one of the most energy-intensive operation performed by equipment fleet (Alshibani and Moselhi 2012). Earthwork is considered as an important operation of which the energy consumption should be predicted and managed. For the accurate prediction of energy consumption of the operation, a planning system, which enables to take into account the characteristics of equipment (e.g., weight, capacity, energy consumption rate of equipment, etc.) and site conditions (e.g., geometric information, attributes of hauling material, road condition, etc.), is necessary for the planning of the low-energy consumption earthwork operation. Identifying an optimal equipment fleet is important to achieve low-energy operations. Hence, this study develops a computerized system which identifies an optimal earthmoving equipment fleet that minimizes the amount of energy consumption in the earthwork operation.

B. Research Procedure

The earthwork operation is performed by diverse combinations of construction equipments. For instance, dozer, pusher/scraper and loader/truck may be utilized depending on the haul distance. The most economical combination of equipment fleet depends on the haul distance (Peurifoy et al. 2009). This study develop 1) a standard earthwork operation model, 2) a method which computes energy consumption of construction equipments used in the earthwork operation, and 3) a computerized system which establishes low-energy consumption plan for the earthwork operation.

II. LITERATURE REVIEW

Existing researches relative to reducing energy consumption are mostly make use of life cycle assessment (LCA) and identify the environmental contamination attributed to construction activities (Bilec et al. 2006, Sharrard et al. 2008). Given the complexities of interactions between construction processes, LCA represents a comprehensive approach to examine the energy consumption and environmental impacts of an entire building project (Tsai et al. 2011). However, most current LCA tools for the entire life-cycle of a building overlook or improperly address the energy consumption and environmental impact from construction processes (Ahn 2012). Only few researchers assess the environmental impacts of construction processes and/or operation and propose methods that assess the energy consumption and environmental impacts attributed to construction operations to complement the existing LCA based methods (Ahn et al. 2010, Gonzalez and Echaveguren 2012, Ahn and Lee 2012, Hasan et al. 2013, Yi et. al 2015). These researches have contributed to identify optimal resource assignment plans for an equipment intensive operation and pursued to estimate the amount of energy consumption according to the states of equipment. The new method improves the accuracy of existing methods by taking into account material attributes and the conditions of specific sites.

III. EARTHWORK OPERATION PLANNING METHOD FOR ENERGY-SAVING

A. System Architecture

The developed system provides a method which finds low-energy consumption equipment fleet taking into account contributory factors in the energy consumption of

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construction equipment (e.g., empty and loaded weight, capacity, hourly fuel consumption rate, etc.), site conditions (e.g., geometric information, material characteristics, road conditions, etc.) and operating conditions of equipment. The operating conditions of equipment are categorized into five modes (i.e., idle, low, medium, high and acceleration), in which the energy consumptions of equipment can be more accurately estimated at different modes of machine operation (Yi et al. 2015). The system consists of datasheets and sub-modules, as follows:

1. Equipment datasheet which contains equipment characteristics such as equipment category, type, hourly cost and hourly fuel consumption rate according to the working conditions. The information is originally provided by Caterpillar (2010).
2. Earth and rock (bank weight, loose weight, and swell factor) property datasheet and rolling resistance data according to the road types.
3. Modelling module which enables to develop operation models in graphic user interface.
4. Sensitivity analysis module which investigates potential optimal equipment fleets achieving low-energy consumption by executing simulation experiments and estimating performances of time, cost and energy consumption required in the associated operation. Detailed procedure of the proposed method is presented as follows.

B. System Algorithm

1) Modeling: A user identifies operation processes and resources required to perform the operation for the modelling of a construction operation. Then, the operation model is developed by establishing the relationships among modelling components and initializing input variables of components. Basic work tasks are defined by using *Combi* or *Normal* components and resources are defined by using *Queue* components. The modelling procedure using discrete event simulation is entailed in other literatures (e.g., Halpin and Riggs 1992, Lee et al. 2010). After developing an operation, a system user defines the quantity and characteristics of materials to be handled in order to calculate loading times and speed of hauling equipment. The system calculates performance of equipment according to the properties of materials defined as shown in Table 1 (Peurifoy et al. 2009). Given the characteristics of road, the system calculates rolling and grade resistance. These values are used to initialize time delay functions of work tasks. The works task times are calculated by using the production equations presented by Peurifoy et al. (2009).

2) Sensitivity Analysis: The system executes simulation experiment using available resource types. A series of simulation experiments is executed by initializing different resource combinations, calculating performance indicators (i.e., time, cost, and energy usage), and saving the simulation output data in every simulation iteration. The simulation output data is generated by considering entity flows and logics in the simulation system. Finally, the simulation outputs are saved and presented.

3) Simulation output analysis: After performing sensitivity analysis, system user may query an optimal resource combination for an operation plan under study. The system finds an optimal resource combination that meets the user defined limitations and priority among performance indicators.

TABLE I
REPRESENTATIVE PROPERTIES OF EARTH AND ROCK

Material	Bank weight (kg/m^3)	Loose weight (kg/m^3)	Swell factor
Clay, dry	1,600	1,185	0.74
Clay, wet	1,780	1,305	0.74
Earth, dry	1,660	1,325	0.80
Earth, wet	1,895	1,528	0.80
Earth and gravel	1,895	1,575	0.89
Gravel, dry	1,660	1,475	0.89
Gravel, wet	2,020	1,765	0.88
Limestone	2,610	1,630	0.63
Rock, well blasted	2,490	1,565	0.63
Sand, dry	1,542	1,340	0.87
Sand, wet	1,600	1,400	0.87
Shale	2,075	1,470	0.71

IV. SYSTEM VERIFICATION

The earthwork operation model, which is consisted of pusher and scraper processes, is presented in Figure I. The test case is an earthmoving operation which is performed by cutting and loading at cut area, hauling the material, dumping the material at fill area and returning to be loaded (Peurifoy et al. 2009). The work tasks of scraper cycle are Load, Haul, Dump, Turn fill, Return, and Turn cut. The work tasks of pusher cycle consist of Contact, Load, Boost, and Position.

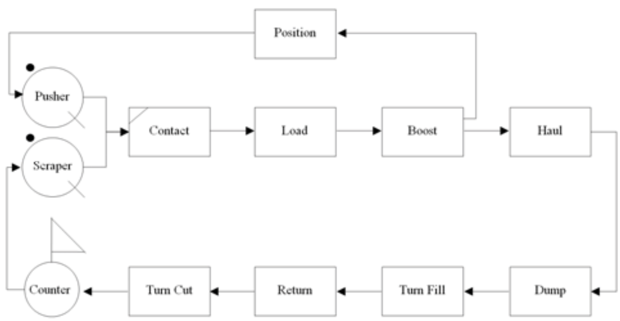

FIGURE I
PUSHER-SCRAPER EARTHMOVING OPERATION MODEL

The task times, operating conditions and involved equipments under study are initialized as shown in Table II. Total amount of material to be moved from cut to fill area is $1,860m^3$ of clay (wet, bank weight is $1,780kg/m^3$, loose weight is $1,305kg/m^3$ and swell factor is 0.74). Available resource ranges are 1 to 20 of scrapers and 1 to 10 of pushers. In addition, the properties of pusher and scraper under study are shown in Table III.

TABLE II
ECONOMICAL EARTHMOVING EQUIPMENT BY HAULING DISTANCE

Work task	Duration (min.)		Operating condition	Involved equipment
Contact	0.10		Low	Pusher
			Idle	Scraper
Position	0.34		Medium	Pusher
Boost	0.15		High	Pusher
			Low	Scraper
Load	0.85		High	Pusher
			Low	Scraper
Haul	3.30	0.45	High	Scraper
		1.14	High	
		1.14	Medium	
		0.43	Low	
		0.14	Low	
Dump	0.37		Medium	Scraper
TurnFill	0.21		Low	Scraper
Return	1.73	0.21	Medium	Scraper
		0.56	Medium	
		0.48	Low	
		0.34	Low	
		0.14	Low	
TurnCut	0.3		Low	Scraper

TABLE III
RESOURCE ATTRIBUTES

Resource Name	Model	Average Fuel Consumption(*l/hour*)					Cost (*$/hour*)
		Idle	Low	Med.	High	Acc.	
Pusher	Track Type D10R	19.69	51.50	67.50	84.50	196.89	125
Scraper	631E Series II	16.50	42.50	56.00	75.00	165.00	101

The system calculates ranges of performance indicators as [36.49:701.00] *min*, *$* [1570.48:15784.18], and [797.91:2929.76] *l* of energy consumption using the 200 simulation outputs. The most energy-saving resource combination is five scrapers and one pusher. A system user can find optimal resource combination not only based on energy consumptions but also operation time or cost.

V. CONCLUSION

This research develops the new energy saving method for the earthwork operation by using discrete event simulation. The contributions can be summarized as follows: First, standard earthwork operation model (performed by pusher-scraper) is presented. This reduces the modeling efforts since users only need to specify minimum modeling requirements such as material attributes and site condition in future modeling work. Second, this study increases the accuracy of predicting energy consumption by categorizing operating conditions, material attributes and site conditions. Finally, the system enables to find an optimal resource combination (i.e., equipment fleet) which minimizes energy consumption of the operation by executing sensitivity analysis. The system is expected as an effective decision-making support tool to predict and manage the earthwork operation.

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