RESEARCH

A STUDY OF THE CONCEPT OF DYNAMIC EQUIPMENT IN THE EARTHMOVING PROCESS BY A CONSIDERATION OF TIME, COST AND EMISSIONS

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ABSTRACT

The earthmoving process is usually handled by a combination of multi-functional excavators and delivery trucks. According to the principles of excavation, a specific machine is selected to dig the earth. Sometimes, due to the difficulties in the process, the digging process is split between different machines with different capabilities. This paper aims to introduce the concept of dynamic equipment for allocating different tasks in an operation to a machine. This concept is discussed and modelled via a discrete-event simulation method and is tested in a real earthmoving operation from three different perspectives: time, cost and emission. The results from the case study show that the use of dynamic equipment will lead to a decrease in cost and emissions and an increase in productivity.

KEYWORDS

CO_2, Earthmoving, Simulation, Discrete-Event, Productivity

INTRODUCTION

Construction activities cause environmental pollution and emit greenhouse gases (GHG), which contribute to global warming [1]. As a result, carbon footprint minimization on earth is seen as a global priority [2]. The construction industry plays a significant role in GHG emissions. It is responsible for 36% of the energy related CO_2 emissions in industrialized countries [3]. For instance, the construction industry with 6% of total industrial-related GHG emissions, is the third top emitter in the United States [4]. In Europe, buildings through construction, use and demolition, contribute almost 50% of the CO_2 emissions released in the atmosphere, which is the basic gas responsible for the greenhouse effect [3, 5].

Previous findings demonstrate the environmental impact of building construction and its relationship to CO_2 emissions in the context of current construction practices [6, 7]. Negative environmental impacts due to CO_2 emissions from the transportation and on-site use of construction equipment have been verified [8]. To tame energy consumption and mitigate emissions, it is urgent for contractors to modify their current construction practices [9].

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As Heydarian and Golparvar-Fard (2011) [10] assert, the challenge for construction firms is reducing the carbon footprint of operations without affecting either productivity or the final project cost.

Among available alternatives, minimizing the down time of construction equipment would result in the reduction of fuel consumption and the extension of engine life. If the equipment is rented, reducing the downtime can reduce the rental fee and the cost associated with the labour.

From a contractor's perspective, better operation planning and less idle time will improve construction productivity. This in turn can lead to significant savings in time and money [11].

The capability of equipment to operate in various combinations was examined in this research. The aim was to compare the carbon footprint of flexible combinations of equipment for carrying out the same amount of work. Moreover, the so-called "Conventional" situation where each task is allocated to a single machine is compared with "Dynamic" situations where various tasks are simultaneously allocated to one machine.

This study was seeking to prove the hypothesis that there is an opportunity to raise productivity with a drop in cost and emissions if the concept of dynamic equipment is applied in the design of the earth moving process

LITERATURE REVIEW

Effective construction equipment practices can minimize equipment downtime. There is much research in the literature concerning this problem, but almost all emphasize machine breakdown. Nevertheless, to date, few efforts have been made to study the effect of factors such as equipment management practices on downtime, which control the dynamic behaviour of the system [12]. Prasertrungruang and Hadikusumo (2009) [13] studied heavy equipment management practices and downtime in large highway projects using system dynamics. Complex earthmoving projects require heavy and costly equipment. Effective utilization of equipment will lead to considerable savings in both cost and time [14, 15] Yet still the concept of dynamic equipment has not clearly been considered in the related literature. In terms of optimization, it is feasible to model the earthmoving process in mathematics and expect that optimization will give us the optimum solution. However, this paper does not seek to find the optimum combinations of tasks via optimization techniques; this issue will be addressed in a future study. Nevertheless, the main aim of this paper is to show the feasibility of having dynamic equipment in earthmoving, and its effects on cost, time and emission.

Abou Rizk (2010)[16] summarized the role of computer simulation in construction projects over the past two decades. The simulation process was divided into four phases: product abstraction, process abstraction, modelling and experimentation. Symbolic elements were used for better communication and simplifying the process. He expressed that possibly the simulation results help a manager to understand the behaviour of the complex process, lowering project costs, shortening durations, improving quality, and increasing certainty in project delivery. The discrete event simulation (DES) was selected in order to model the process and study the influences of changing parameters on the system. In advanced modelling techniques such as discrete event simulation (DES), the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system [17]. DES models describe systems evolving over time, where state variables change instantaneously at separate points in time. DES models are able to model and handle complex systems with highly dynamic decision rules and relationships between different

entities and resources, and they explicitly include system uncertainty [17]. In practice, DES modelling allows the simultaneous analysis of any production process involving resources, energy, residuals and/or emissions and helps to develop accurate and representative models of processes and thus quantify their sustainable (and environmental) behaviour.

In construction, DES modelling has been given a significant amount of attention, and during the last three decades, researchers have developed several simulation tools and engines to model and optimize construction operations[16]. The simulation of construction operations using the DES approach involving earthmoving operations such as excavations, loading, hauling and dumping has also been a specific concern of several researchers [16, 18-24]. However, the study of a project's environmental effects has not received much attention in construction as yet, except for some recent studies that have focused on the analysis of emissions in construction projects using DES modelling techniques and environmental models [25-28] One interesting finding provided by these studies was the demonstration that emission estimates using the traditional Life Cycle Analysis (LCA) approach or the integration of emission models and standard bills of materials can be improved with DES techniques. In this paper the DES is used as a modelling tool to analyse the effects of dynamic equipment on the system.

METHODOLOGY

Construction planning is the most crucial, knowledge-intensive, ill-structured and challenging phase in the project development cycle due to the complicated, interactive and dynamic nature of construction processes[15]. Earthmoving as a machine intensive operation plays a principal role in construction in terms of emissions and cost. Reducing the rate of idleness in earthmoving fleets is an important goal for managers and one that is seriously considered in the design stage of an earthmoving process. Except for the trucks in earthmoving process, the rest of the machinery is multi-functional. For example, a hydraulic excavator can dig, load and lift in an earthmoving process; a dozer can dig and push. This flexibility inspired the authors to study the concept of using a machine for different tasks in a process.

The machines used in an earthmoving process are interlocked with one another. The output of one machine is the input for the next machine. This requires that the production rates of consecutive tasks are very close to each other. Otherwise any significant difference in the production rates of a set of following machines will lead to increased queueing or idleness in the system.

Technically, in some cases the productivity of a machine is very low and economically it is not cost effective to hire a machine with higher efficiency. Therefore, that particular machine creates a bottleneck in the system and thus the system production rate will be dominated by the production of that machine. This means the production rates of the following machines will be limited to the production rate of the slow machine. This means a part of their capacities are wasted.

In such situation the concept of dynamic equipment is really understood. A dynamic machine can handle several tasks, so there is no need to allocate a machine per task. Although it is expected to provide a cut in costs, the working time of the dynamic machine increases, resulting in the production of more CO_2. Consequently, for holistic decision making in terms of adopting dynamic equipment in the design of earthmoving process, in addition to time and cost, emissions must also be investigated.

The proposed model considers not only typical time and cost performance indicators in the process of construction operation design but also considers the environmental concern of emissions. The methodology includes three stages. First the emission factor is calculated using the EPA model (EPA 2004). Then, using Stroboscope [23] the process will be simulated and equipment durations shall be calculated. Next, the previous sections will be combined and the carbon footprint will be calculated. Finally, it is implemented to find the optimum decision in terms of minimizing cost, time and emission.

CASE STUDY

In order to test the feasibility of the proposed concept a commercial building project located in the Sydney metropolitan area was selected as a case study. The foundation elevation being 12 metres below the ground level required more than 14000 m3 of ground being excavated and hauled to a dumping spot 20 kilometres away from the site. Geotechnical tests reported that the project was on a layer of sedimentary rock. So, two hydraulic excavators equipped with hammers were hired to crush the rocks. Then two other excavators removed the crushed rocks from the field and clean the area for the next crushing process. After that, a bulldozer collected the excavated rocks around the machines, pushed the material to the corner of the site where a hydraulic excavator is positioned 3 metres above the excavation field, and lifted the crushed rocks to an elevation of 8 metres above the field. Finally, another hydraulic excavator loaded the excavated materials to the trucks.

Massive fleet, multi-functional applications and interlocked sub-cycles made this a difficult case to manage. Therefore Stroboscope was used to model this complex earthmoving process as illustrated in (Figure 1). The process was virtually divided into the three sub-processes: excavation, soil gathering and loading-dumping. "Excavation" consisted of rip and

FIGURE 1. *Stroboscope* model of conventional situation.

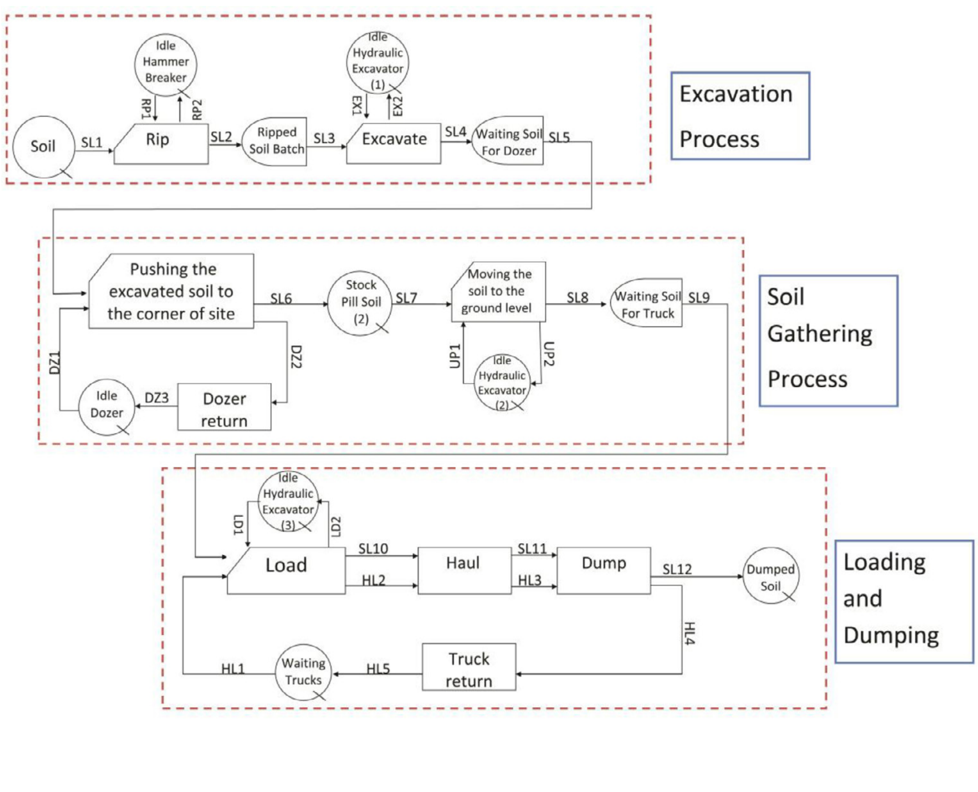
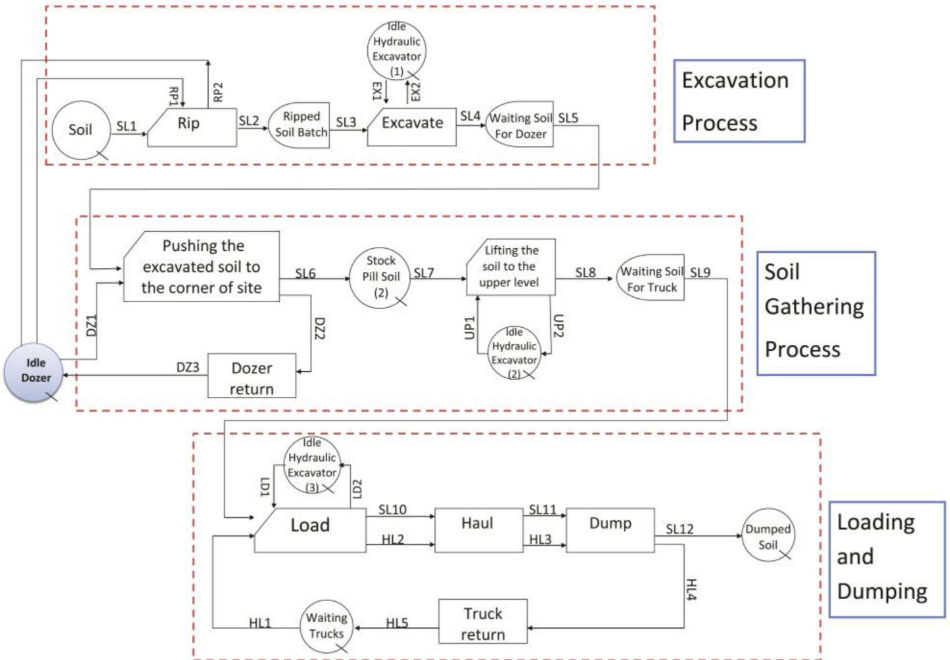


FIGURE 2. Revised simulation model by adding a resource pool which is share between rip and push.



excavation, which was performed by excavators and bulldozers. "Soil gathering and deposition" was carried out by bulldozers, and finally excavators and trucks were involved in "loading and dumping".

Through observations of the earthmoving process, data regards to cycle times were recorded. Appropriate probability distribution function (PDF) for each acquired time set was obtained statistically. The Chi-Square method is applied for goodness of fit during picking the PDFs. Then the PDFs are embedded into the simulation model. Simulation results were consistent with actual data and the model was validated with a reliable level of confidence. Observed errors initiated from process complexity and probability distribution fitness were assessed to be insignificant. Therefore, the built simulation model is valid for future study.

According to the collected data, it was perceived that the available dozer on site can be used in other roles rather than pushing. For instance, because a dozer has a ripper at its back, it can also be used to break the rock. Moreover, it was realized that ripping by dozer is significantly faster than by hammer. Therefore, it was decided to allocate the ripping task to the dozer as its second job. This meant that the dozer was defined as a dynamic resource which could handle both tasks of rip and push on site (Figure 2). Therefore, the dozer must be moved dynamically between these two tasks; however, in the cases that both tasks require the dozer, the priority is given to the rip because it is the first task in the system.

RESULTS AND DISCUSSION

Simulation

The achieved results from the simulation models show that just by sharing the dozer between Rip and Push the productivity will be increased more than expected and the system works

more smoothly. It indicates that a shared dozer between Rip and Push will work better than would be the case if Rip and Push were handled by two machines. The following graphs in this section illustrate in two time scales in order to study the behaviour of system under the new changes in more detail

As Figure 3 shows, the productivity rate of the Rip and Push tasks are approximately consistently similar; this means that the dozer can balance both jobs. Moreover, the allocated hydraulic excavator also can excavate the ripped soil at the same rate as the Rip and Push tasks. So, it seems that the first part of process which was formerly called "Excavation Process" works smoothly. In Figure 4 the tasks of Lift and Load are examined in controlling parts of the process. Also, due to the space limitation at the site for lifting and loading which can use a maximum of one machine for each of these two tasks, the productivity of this sup-process cannot be increased technically. Therefore, the amount of waiting soil for Lift and Load is increased by time (Figure 4). For the Haul and Dumping, the optimum number of trucks is 10; with this number the production rate is very close to the expected productivity of Lift and Load that are the bottleneck of the system. So, the simulation model shows that by sharing a dozer between two tasks a higher rate of productivity than might otherwise be expected can be achieved.

Cost Analysis

In order to compare the cost of the conventional pattern with the dynamic pattern, the overall cost per day for a dozer is set as the reference cost and the cost of other equipment is calculated based on the daily cost of a dozer.

All the daily costs, obtained from the earthmoving contractor, include equipment hire, fuel, maintenance and the drivers' wages. Furthermore, because all tasks including rip, excavate, push and load are done by hydraulic excavator, it can be assumed that the cost of a dozer for one day be A. By comparing the cost of other equipment to dozer daily cost (A), a proportion

FIGURE 3. Behaviours of each entity achieved from simulation model.

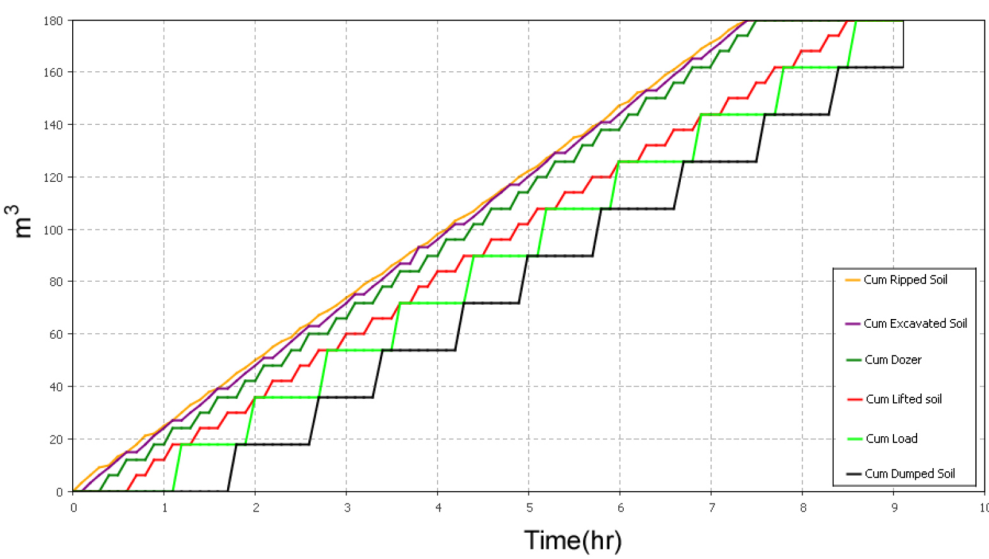


FIGURE 4. Amount of waiting soil for Excavate, Lift and Load.

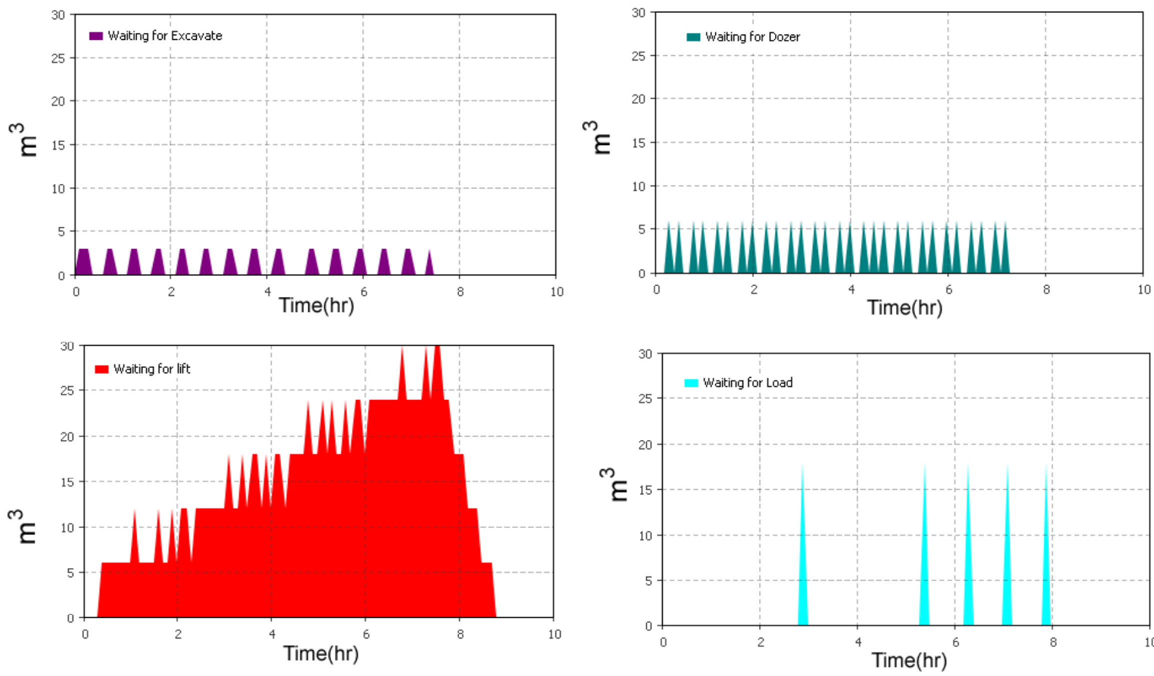


TABLE 1. Cost Comparison.

	Conventional pattern		Dynamic pattern	
	Quantity	Cost/Day	Quantity	Cost/Day
Ripper	2	0.52 A	0	0.52 A
Excavator	1	0.47 A	1	0.47 A
Dozer	1	A	1	1.15 A
Lift	1	0.40 A	1	0.40 A
Load	1	0.40 A	1	0.40 A
Truck	10	0.70 A	10	0.70 A
Sum		**10.31 A**		**9.42 A**

of A is defined for daily cost of each equipment. Then, the costs of conventional fleet pattern and the dynamic pattern in which the dozer plays two roles can be identified (see Table 1).

From an economical point of view, the implementation of dynamic equipment in simulation leads to the improvement of the system production rate and a drop in overall cost, however, a non-environmental friendly machine with a very high rate of fuel consumption was used more. This change in the earthmoving system might lead to a significant rise in the amount of produced CO_2. So, in the next section the environmental impacts of using dynamic equipment in the case study are investigated.

Carbon footprint

The EPA model was used to compare the emission production in a conventional pattern with the dynamic pattern. Emissions from the use of equipment are determined by a product of emission rate and predicted operation time of each piece of equipment.

$$\text{Emission} = \text{Emission rate} \times \text{operation time} \qquad \text{(eq.1)}$$

The emission rate of diesel equipment can be derived from Environmental Protection Agency's *NONROAD* model (EPA 2004), which provides an off-road engine emission inventory. The EPA model calculates emission rate for CO_2 based on parameters which depend on the engine power (hp) and the model of the machine engines (eq. 2). As the equation shows, the actual duration the machines have worked is also required to calculate the amount of emitted CO_2.

$$\text{Emission rate } (CO_2) = (BSCF \times 453.6 - HC) \times 0.87 * (44/12) \qquad \text{(eq. 2)}$$

Where CO_2 is in g/hp-hr, BSCF is the infused adjusted fuel consumption in (lb/hp-hr), 453.6 is the conversion factor from pounds to grams, HC is the in-use adjusted hydrocarbon emissions in (g/hp-hr), and 0.87 is the carbon mass fraction of diesel and 44/12 is the ration of CO_2 mass to carbon mass. Both BSCF and HC are derived from the zero-state steady state emission factor (EFss) which is based on engine horsepower and year of make.

$$BSCF = EFss \times TAF \qquad \text{(eq. 3)}$$

$$HC = EFss \times TAF \times DF \qquad \text{(eq. 4)}$$

Where TAF is the unit less transient adjustment factor (TAF) and DF is the deterioration factor (DF), and based on eq. 1, the information required to calculate the emission saving from this combination improvement is presented in Table 2.

TABLE 2. Machine description.

		Time (hr/ day)	
Machine	**Description**	**Conv. Pattern**	**Dynamic Pattern**
Excavator	Hp: 204 Year: 2002	18	0
Dozer	Hp: 580 Year: 1995	0.3	0.84

The duration of excavator for dynamic pattern is zero, because in dynamic pattern the excavators will not be hired and their task will be assigned to the dozer. Based on Table 2 the emission factors of BSCF and HC were calculated for both machinery combinations and the overall CO_2 emission of each combination was calculated (see Table 3). As is shown, by modifying the combination through a 30 day working period 54 tons of CO_2 is saved.

TABLE 3. Carbon footprint calculations.

	BSCF (lb/day)	HC (lb/day)	CO_2 (g)
Conv. Pattern	1425.597	1222.198	61,767,509
Dynamic Pattern	180.769	103.334	7,837,232

The benefits of adopting the concept of dynamic equipment in the design of earthmoving processes was demonstrated through a case study. It was shown through discrete event simulation that by assigning dynamic tasks to equipment instead of allocating separate tasks for different equipment, higher productivity is achieved, the cost is reduced by 8.6%, and the total emission is reduced by 54 tonnes.

CONCLUSION

The idleness of fleet in the earthmoving process is a challenge that increases the operational costs. Also, most of earthmoving equipment is designed to handle different functions. So, the concept of sharing a multi-functional machine between different tasks is introduced in this paper, and its feasibility was considered in a case study which looked at the changes in time, cost and emission. The implementation of dynamic equipment might lead to a drop in costs with a larger amount of produced emission. A complex earthmoving process was selected for the case study and its simulation was modelled. Based on the collected data, the simulation model was validated and then the concept of dynamic equipment was implemented by allocating two tasks to a machine in a dynamic pattern. The results demonstrate that this change in system will lead to increased productivity and a valuable drop in cost and emissions that can be applied in earthmoving operations.

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