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Eco-economic excavator configuration method

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ABSTRACT

Excavating processes performed frequently in building, civil and infrastructure projects are critical and costly. To define a cost-effective excavator configuration, an earthwork planner depends mostly on experience and intuition. This intuitive reasoning is often error-prone, and highly experience based. This paper presents a computational method called the Eco-Economic Excavator Configuration (E3C), which selects the most favorable configuration of a heavy duty excavator according to the earthwork package and its job conditions. E3C obtains the input data from external databases, derives the formulae involved in computing the process performance (e.g., production rate, process completion time, and profit), and instructs the earthwork manager in the best-fit excavator configuration (e.g., maximum digging depth, engine size in HP, and bucket size) for profitable operation by considering the implicit constraints and conditions exhaustively. The method identifies the best-fit PDFs of the process completion time and that of the total profit, given an excavator configuration. A test case, which was performed at a building basement excavating project, confirmed the usability and validity of the method.

1. Introduction

Excavation, which initiates the processing entity (i.e., a rock-earth volume) in an earthwork operation, requires hydraulic heavy duty excavators. These include a front shovel, back shovel (or hoe, backhoe), loader, and specialty excavators (e.g., trencher, backhoe-loaders, etc.), which require great financial investment. A backhoe is used for digging below the track level (e.g., the bottom of the running gear), such as pits for basement. This is a boom and stick downward swing machine mounted on either the crawler or pneumatic-tire with a range of working attachments and engine configurations. The eco-economic performance of a hoe varies according to the configuration of the machine attributes (i.e. maximum digging depth, engine capacity in horse power (HP), and bucket size, etc.) of an earthwork package (e.g., the unit price commissioned, target duration, daily working hours, total volume of work, and average digging depth). The best-fit configuration of a machine's attributes that maximize the total profit of the excavating process can be identified by considering the work package information and other attributes involved in soil (e.g., soil type, volume conversation factor, rock-earth handling difficulty, etc.), job site (e.g., grade, rolling, and penetration resistances), and management (e.g., desired productivity, efficiency, cycle time, and the interval between trucks.) jointly. To assure the most favorable cost performance, the following should be considered: cash inflow, and outflow items (e.g., the ownership cost, operating cost, and the daily indirect cost), which are subject to the transitory nature of operating conditions on a job site.

After enforcing the Tier 4 interim emission regulations in 2011, an eco-economic operation has become a highly critical issue to the earthwork community. Equipment fuel consumption is almost double the levels suggested by the US government alone [1]. According to a rental rate survey conducted by the State of California (2015), the hourly rental rates of hydraulic crawler excavators (e.g., KOMATSU-9575LC), which include all the attachments required for digging, can be $US 516. Fuel and oil consumption comprise a large portion of the cost in excavating jobs. Certainly, reducing fuel consumption is an important issue for reducing the process completion cost and alleviating the environmental burden. Identifying the most favorable machine configuration involves many different sources of data, as well as sophisticated and repetitive computations using these sources. They include the earthwork control account information under study; excavator database of which each record maintains a maximum digging depth, a maximum dumping height, engine capacity, and set of buckets attachable; the historical performance data of each equipment, including its fuel and oil consumption; job site conditions; and work characteristics. Indeed, collecting the required information from many different sources in time and identifying the optimal solution on a manual basis depending on intuition is time consuming, error prone, and expensive. A well experienced earthwork manager may require

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several hours to complete the entire data compiling and decision process. To increase the eco-economic performance, the values of the variables that influence the excavator's cost performance should be determined and analyzed in real time.

When an excavator digs a new face, i.e., cell or pit, on a job site, the soil rock layers of the cell vary according to the different external variables, i.e., job site attributes and geologic-geotechnical attributes, thereby requiring a new equipment configuration with a different working attachment. On the other hand, no study has provided mathematical methods that handle the transitory nature of the external variables and adjust the bucket-excavator configuration. Certainly, it is essential for the earthwork management arsenal to equip a new computational method that identifies the most economical bucket-excavator configuration. The method should include functions that collect and analyze the values that influence the excavator's internal and external system variables, which affect the excavator's eco-economic performance adversely in real time using smart sensors; record the data into a database; computes rapidly the cycle time, as well as the time, cost and profit performance of each excavator configuration of the engine (e.g. type and size), maximum digging depth, and bucket configuration; identify the optimal machine configuration; and handle the variability of the process completion time and that of the process completion profit with the configuration. Indeed, such a method may provide a tool to control the economic excavating and fuel efficiency.

2. Current state of excavator configurations and selection

2.1. The cycle time of hydraulic backhoe

An excavator is a versatile equipment that performs various tasks (e.g., digging pit, cutting face, loading, unloading, trenching, lifting, etc.). The machine is a "self-propelled machine on crawlers or wheels with an upper structure capable of a 360° swing and primarily designed for excavating with a bucket" of which the work cycle comprises digging, swing to dump, discharging, returning to digging, repositioning to a new face, and idling [2]. Given a standard excavation job, a heavy-duty ditching bucket is used for a variety of rock-earth conditions (e.g., clay, gravel, sand, and silt, etc.); a severe-duty ditching bucket is used for handling abrasive materials in a severe digging and truck-loading process.

The productivity of an excavator is quite sensitive to the cycle time. This is the denominator of the excavator's output formula and a direct measure of the equipment performance represented by the constant dictation of each and every motion of an excavator at the excavating process level. Measuring the cycle time of an excavator is essential for planning and controlling its productivity. Edwards and Holt [3] proposed a model that calculates the cycle time and unit costs of a hydraulic excavator using three predictors of the cycle time (i.e., machine weight, digging depth, and machine swing angle), which was obtained by multiple regression analysis hybridized with chi-square and Pearson correlation coefficient. Tam et al. [4] identified the two sets of controllable and uncontrollable excavator productivity variables and proposed a model that estimates the excavator's cycle time and predicts its productivity using artificial neural networks. Yang et al. [5] improved Edwards and Holt's [3] study by implementing a stochastic simulation that embeds fuzzy model algorithms. The model forecasts the cycle time by incorporating additional operation parameters (e.g. machine configuration, ground conditions, operator competency). These conventional cycle time measurements are subjective because they predict the cycle time using quantitative models implemented using project-specific historical data. Subsequently, high-tech excavator guidance systems carry innovative sensors that allow real-time simultaneous transmission and the reception of operation parameters (i.e., depth, grade, swing, position, etc.). They encourage the accumulation of historical operation data; hence, they provide a source from which the times of the excavator motions (i.e., digging, swing to dump, dumping, returning to digging, repositioning to a new face, and idling) can be computed. Rezazadeh et al. [6] proposed a computer vision algorithm that detects earthmoving equipment (i.e., excavator and trucks), and measures their loading cycles in real time. Pradhananga and Teizer [7] presented a method that makes use of global positioning system (GPS) devices installed into earthwork equipment. The algorithm records the historical cycle times by executing a series of computational tasks, each of which recognizes the object spatial coordinate in job site space, locates the earthwork equipment in real-time, and identifies the flow of equipment motion lines on the job site coordinate. Indeed, the conventional cycle time estimation methods are replaced with physical measurements that produce historical motion data by locating the equipment position in timestamps. In particular, the cycle time measurement uses the locations of the excavator and the earthmoving truck. These new methods improve the accuracy of the productivity prediction, thereby helping to improve the decisions to plan, manage, and control earthwork tasks. On the other hand, the physical measurements have not reached sufficient maturity because they are still measured indirectly. Therefore, it would be desirable to measure the motions of each part of an excavator (i.e., bucket, stick, boom, and cabin) directly using wireless sensors and classify its motions using the sensor streams of motion events. This may improve the accuracy of the cycle time and productivity, thereby helping to select the optimal bucket-excavator configuration.

2.2. Existing computer-aided earthwork equipment fleet selection

Identifying the most favorable excavator-truck fleet combination is the most important decision that contributes to the productivity of an earthwork operation system. The complex and dynamic nature of excavating jobs encourages the development of computer-aided earthwork modeling and analysis methods (linear-integer programming, queuing theory, and simulation) hybridizing with an advanced artificial inference techniques (genetic algorithms, neural networks, and fuzzy inference) to find the optimal solution. Linear programming was used to select the best-fit excavator type, given the mass excavation production scenarios [8]; queuing theory and simulation to handle the uncertainties of earthmoving operations [9]. Simulations help maximize the productivity of an excavator-truck fleet; determine a realistic estimate for the number of loads; incorporate a user-defined number of trucks, truck type, material type, haul distance, excavator type, and excavator and truck availability; and optimize earthmoving operations by hybridizing with genetic algorithms (GA) [10].

The existing methods are well established and available in theory and application at the earthmoving operation level. On the other hand, it would be desirable to provide a computational method that considers the variability of the eco-economic performance of an excavator, which varies with the configuration of its maximum digging depth, bucket size, and engine size; considers the stochastic natures of the excavating cycle times; incorporates the data source of those twenty variables associated with four criteria (contract, job site, machine, and geologic-geotechnical) with a simulation; integrates the demands of the processing entities by an external earthwork operation model; and estimates the variability of the process completion time and process completion profit by providing an automated easy-to-use interface. Indeed, the maximum digging depth, engine size, and bucket size can be configured by considering these parameters thoroughly. This may improve the eco-economic excavating performance by providing the most favorable configuration option (the optimal set of maximum digging depth, engine capacity, and bucket size) and help ensure the maximum profit by drilling down into the motions of an excavator at the excavating process level.