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Selection of heavy machinery for earthwork activities: A multi-objective optimization approach using a genetic algorithm

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Abstract Earthmoving activity is considered one of the most critical elements in construction projects. The overall cost of earthmoving activity during construction projects can account for more than 30% of the total cost. Moreover, earthmoving equipment emits enormous carbon, which has adverse environmental effects. A mathematical model is needed to optimize the selection of the equipment types (i.e., trucks and excavators) and the numbers of each type to be employed on a particular project, based on the work capacity of each unit, the number of units, and the speed at which each unit travels. The model proposed here is based on a genetic algorithm (GA) based optimization technique for planning earthmoving projects. The model has three main steps: (1) identify all the relevant decision variables for choosing the earthmoving equipment, (2) derive a mathematical optimization model, and (3) apply multi-objective genetic algorithms. For a particular selection of earthmoving units, the model can show how the total project costs will vary concerning the time allowed to complete the project while also providing data showing the total amount of carbon emissions and fuel consumption for the entire project. Data derived from a real-world earthmoving project was employed to test and validate the model. The model was able to show the potential for saving substantial cost and time. On average, the optimization model showed how to obtain

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savings of 14.35% and 9.5% for the time and the cost objectives, respectively, along with significant reductions in fuel consumption and CO_2 emissions. These results suggest that the proposed optimization model would be a valuable tool to support contractors and construction management engineers to minimize earthmoving projects' time and cost.

1. Introduction

Earthmoving equipment refers to large self-powered machines used during civil construction projects [1]. Proper management of this equipment is crucial in all project phases [2]. Construction firms have sometimes been forced to declare bankruptcy when they relied on their judgement to select the appropriate equipment for the job, instead of following research-supported approaches or working with a multi-field question team. Construction sites are often populated with a plethora of complicated equipment without relying on any systematic approach to select, control, schedule and monitor the equipment and the processes [3,4].

This research seeks to develop an effective and innovative multi-objective and multi-variable optimization model for earthmoving projects that can provide optimal outcomes, by minimizing the project's cost, given the time allowed to complete. Minimization of time and cost are often competing for objectives for a construction project, making it difficult and challenging to find the optimal tradeoff between these two objectives. Tradeoffs are often suboptimal when planners do not have an effective planning tool to trade off time and cost appropriately.

In some cases, the project time is limited. A short project time can lead to a higher cost. This makes it more challenging and complex to find the optimal balance in such a real world scenario. Moreover, the cost is a significant factor in choosing the contractor in most projects. Faced with increasing competition for construction projects, contractors might be forced to reduce their profit margins to keep themselves competitive in the marketplace. Failure to accurately estimate the cost of a project might reduce their profit margin, forcing the contractor into bankruptcy. Some construction contracts demand that a project be completed within a specified time, or the contractor will suffer financial penalties for the delays. This makes accurate time estimation an essential factor in estimating the total cost [5].

This research takes this time issue into account by (1) deriving a comprehensive mathematical model that considers the equipment speed of the trucks; (2) optimizing the speed, numbers, and capacity of trucks and excavators to maximize the productivity of the equipment, while minimizing the project duration, total cost, fuel consumption and their impacts on the environment; (3) determining optimal tradeoffs between minimizing the time and minimizing the cost of the earthmoving activities; (4) exploring a variety of alternative solutions by using many different combinations of equipment; (5) maximizing the fuel efficiency of the earthmoving equipment used on the project site; and (6) reducing the pollutant emissions of the earthmoving equipment used on the project site. Because of the complexity of this task, an innovative, comprehensive mathematical model is needed.

The current research contributes to the body of knowledge by developing a novel multiobjective optimization using GA to generate time-cost trade offs for equipment in earthmoving activities. The novelty of the proposed model relies upon embedding the truck speed as the primary attribute, which significantly affects the mathematical model complexity and helps address more realistic solutions that decision makers can use to enhance the smoothness of equipment selection within optimized time and cost objectives functions.

The rest of this paper is structured as follows. Section 2 reviews the relevant literature and poses the research question. Section 3 details the proposed mathematical model and the testing and validation of that model. Section 4 presents and discusses the optimization results and the environmental impact assessments. Lastly, Section 5 concludes the paper.

2. Literature review

Many optimization models have been introduced to solve multiobjective problems. For example, a novel evolutionary algorithm based on preference polyhedron theory to enrich the user with a set of optimal solutions was developed [6]. Also, a memetic algorithm for interval multiobjective optimization was proposed to boost proficiency in the convergence process and reduce uncertainty issues [7]. Moreover, the practical optimization model called multiobjective heat transfer research based on the modified binomial crossover (MOHTS-BX) was proposed to reinforce the heat transfer research optimizer [8]. Accordingly, the modified heat transfer search optimizer has a high proficiency compared to other types of optimizers [9]. As a result, these algorithms are suitable for multiobjective functions with contrasting nature [10]. Furthermore, to solve optimization problems with higher-dimensional structural, the Multi-Objective Plasma Generation Optimization algorithm has been implemented. Such an algorithm showed the highest performance as it was initiated by merging, namely excitation, de-excitation, and ionization, with plasma generation to enhance the research in many aspects (i.e., coverage, convergence, and solution diversity) [11]. In the same vein, the novel Multi-Objective Passing Vehicle Search algorithm has been improved to provide optimal solutions for design problems [12]. Additionally, for purposes of improving the speed and convergence rate of the algorithm purposes, multiobjective teaching–learning-based optimization has been proposed [13].

2.1. Optimal equipment selection is vital for the success of the construction project

The conducted studies included but were not limited to, cost estimation, engineering, scheduling, planning, and monitoring, and project control procedures. The goal is to optimize time and cost is using controlled or uncontrolled assets to calculate the optimal solutions considering all project life cycle-related complications [14]. Proper project management should include tracking all equipment, safety, and health aspects. These include equipment maintenance, equipment financing, fuel consumption, driver management, and equipment telematics [15]. If this is done correctly, the owner can maintain and improve efficiency while protecting equipment investments and minimizing the cost of the ownership.

The proper selection of equipment is most important in very large construction projects, where the pace of work is determined by the equipment fleet [16]. In such projects, the equipment fleet can account for the most significant cost [3]. Considerable project delays can result if ongoing equipment maintenance and management are not conducted timely. Contractors often rely on their experience and databases and statistics from earlier projects to guide them in selecting earthmoving equipment for a new project [17]. This approach might be appropriate in the early conceptual stages of the project. However, it is not adequate as a large project progresses into active status. Many techniques might be used to supplement historical data. For example, planners might use manufacturer's data to determine the relative costs of various types of earthmoving equipment. Performance charts might also select fleet equipment based on tradeoffs between budget and schedule. Additional essential factors can be incorporated, such as hazard management, construction equipment planning, control requirements, procedures, downtime management, and repair and maintenance schedules [15].

The productivity of the equipment fleet can be the central aspect in controlling the time and cost of the project [18]. Many promising techniques have been used, such as assimilation programs, analytical models, and optimization models, to minimize the cost and time of earthmoving activities. For example, one model has been used for optimizing the number and capacity of hauling equipment based on the loading facility characteristics. A cost index number (CIN) was used to quantify the optimum haul unit size and number for a given set of loading conditions. The rounding off the haul unit number was also considered during the decision-making stage. A load growth curve was employed to determine an accurate value for the loading time. Loader production criteria were implemented to enhance the haul unit selection decisions. This model used sustained productivity rather than instantaneous productions, which was used on other models. A set of additional criteria were created to spotlight costs, rather than just the physical parameters (i.e., time or production) [19].

The GA was associated with discrete event simulation (DES) procedures to optimize truck dispatch schedules during earthmoving activities to minimize transportation time [4]. This approach can be called a hybrid approach, where DES is implemented to simulate the earthworks operations that would create programs for various Truck dispatching processes. The GA takes the place of the filtering agent to filter out schedules that involve long distances. The GA was implemented to choose from many optimal programs concerning each operation's minimum time. User-friendly software was provided to the firms handling the earthworks transportation to facilitate their operations and offer managers the power to create a well-organized truck fleet dispatch schedule [4]. A study was also conducted to reduce equipment emissions and fuel consumption based on idle times and related activities [20]. An optimization model based on the linear integer number mixed method was implemented to keep equipment emissions of multiple pollutants low and reduce the equipment's total cost [16]. Visual Basic was used to provide an end-user with an optimized earthwork equipment fleet report, based on economic principles, to manage their equipment correctly. Only excavator equipment was modelled. [21].

The GA optimization technique is a practical algorithm with many applications in many construction management problems [22]. These problems include scheduling and resource allocation, construction work area layout [23], and optimizing and selecting earthmoving equipment [24]. Earthmoving activities are complex high-dimensional non-linear processes. This makes finding optimum solutions to earthmoving problems complex [25]. Traditional linear optimization techniques are not efficient in handling these non-linear problems. However, GA techniques are powerful methods for finding optimized solutions to complicated issues. Multiple optimized solutions can be discovered and explored using such techniques implemented with suitable mathematical software.

2.2. Genetic algorithm is useful for Multi-Objective optimization

GAs is better suited to finding optimized solutions to complex earthmoving activity requirements than other traditional optimization techniques [26,27]. GAs employs the principle of "Darwinian natural selection" to develop optimal solutions. GAs have been applied to formulate mathematical models for optimized tradeoffs between the earthmoving objectives' time and cost. The ability and the efficiency of GAs in solving multi-objective and multi-variable optimization problems have been the main reason for tackling this complex research problem [28]. Furthermore, a GA is used to adapt the objective functions' dynamic nature to support the decision-makers with the appropriate tools to solve construction problems [29,30].

2.3. Summary

Selecting and planning earthmoving activities to obtain the required equipment functionality under cost restrictions dictated by a budget and within a predetermined time frame while minimizing emissions is a very complex problem. A planner must evaluate and trade off all these factors to optimally plan a project. Optimization of all these factors will ultimately play a crucial role in the success of construction firms [21].

Despite the substantial contributions of all these previous studies, there are many limitations associated with truck speed determination, which is considered a critical decision-making variable. Speed has a significant effect on costs, including fuel consumption, pollution, and maintenance. A mathematical framework is needed to estimate actual equipment fleet productivity and cost within a workspace influenced by many factors. This research aims to develop a valuable tool to allow contractors to select earthmoving equipment and plan their projects within a specified cost and a predetermined project timeframe. In doing so, fuel consumption and emission reduction are highly considered. Construction project managers must optimize their equipment management process (whether the equipment is already a company asset, whether it will be purchased, or whether it will be rented) to achieve the maximum profit [31].

It is with this in mind that this work poses the following research question:

How could we use a Genetic Algorithm to perform multi-objective optimization to select heavy equipment in construction projects?

3. Methodology

The proposed mathematical optimization model is divided into three main stages: (I) Data Definition; (II) Model Formulation, which is done in four main phases, (a) define all related decision variables for earthmoving equipment, (b) detect all related constraints that impact the optimization model, (c) derive the mathematical optimization model, and (d) Apply GA-based multi-objective optimization. The proposed model is illustrated in Fig. 1. Additionally, (III) Testing and Validation, when the proposed model's efficiency and accuracy are determined and validated.

3.1. Data definition

This stage categorizes the input data into four main categories (fixed costs, variable costs, contract specifications, and equipment specifications). The details of each category are addressed below.

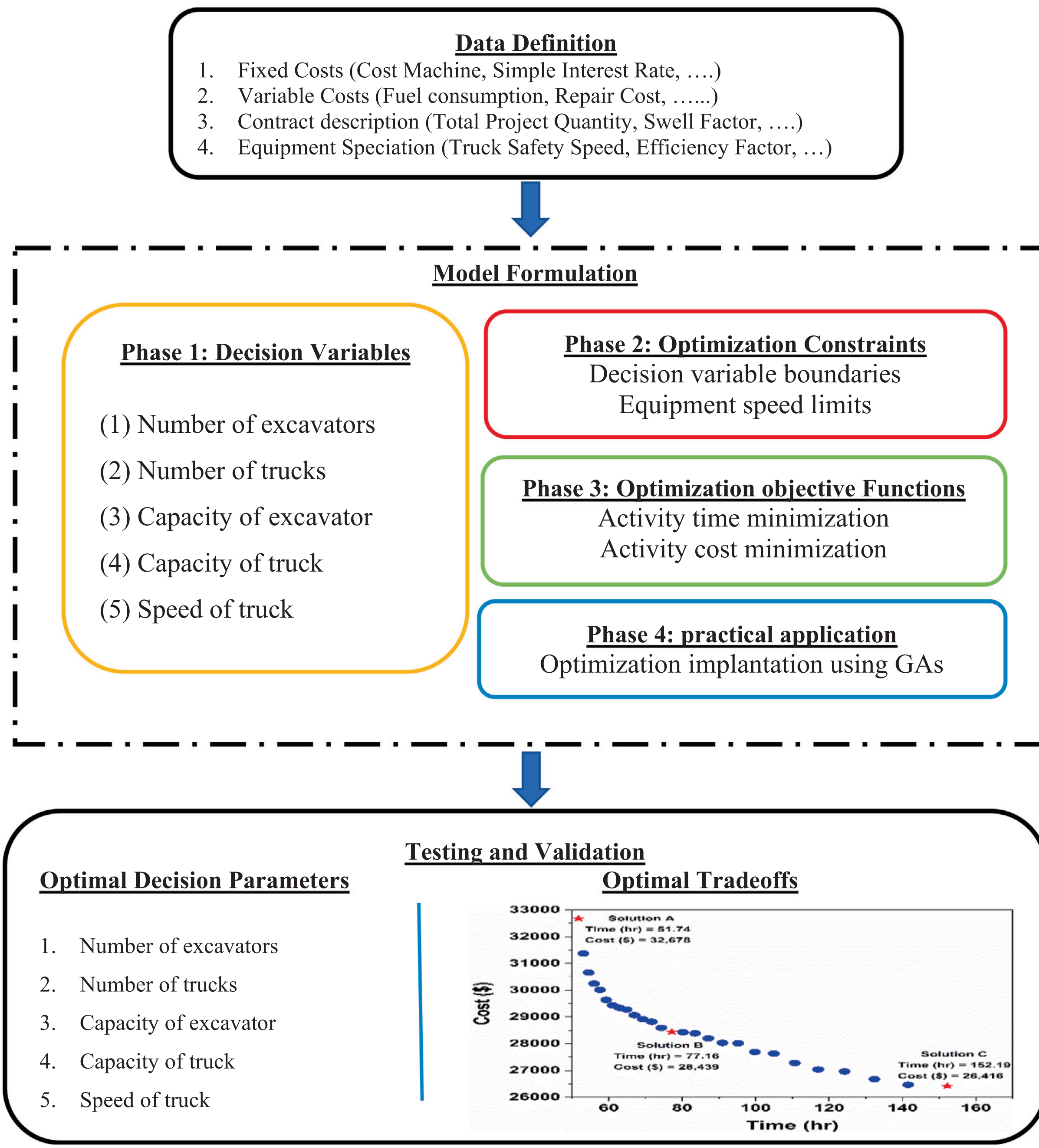

Fig. 1 The proposed approach.

(1) Fixed Costs

Any cost that is not dependent on ongoing activities of the earthmoving process is defined as a fixed cost. Fixed costs will be paid in all cases. Fixed costs could be classified as listed below:

- Equipment Cost (Ch)

This cost is determined by knowing two types of expenses. The machine's net value cost is based on "Delivered Price (P)". It must contain all costs that enable a machine to be ready in the field, transportation and various sale taxes related to that machine. Secondly, "Less Residual Value (Rvr)" is trade-in or resale value. Some construction equipment models have high salvage value, which might reduce total hourly owning costs, decrease the hourly depreciation charges, and enhance the owners' competitive status. This cost depends on the equipment type and second ownership usage in hours [32].

- Simple Interest Rate (Sr)

Simple interest rates are used to calculate the interest cost. The interest costs are costs of creating or owning the assets (such as equipment) during the construction. Interest costs are considered a portion of the hourly operating and owning costs. In other words, they consider interest as part of the overhead cost for the project [33].

- Insurance Rate (Ir) and Tax Rate (Tr)

Insurance rates are used to calculate the insurance cost. This is the cost to protect against theft, fire, accidents, and liability for each of the project's machines. The tax rate is used to calculate tax costs. Tax cost is based on the cost of the license and the property tax for each machine used in the project. The taxes and the insurance costs for each machine in the project are considered annual costs [34].

- Additional Cost (Add)

The additional cost includes the Mobilization, Demobilization, and Supervision cost. Also included is any cost that the contractor incurs because the owner caused a construction delay [34].

- Operator Wages (Ow)

The per-hour operator wage is affected by local wage scales, governmental legislation, and fringe benefits.

(2) Variable Costs

All costs that change as the project progresses are defined as variable costs. There are many variable cost items in any construction project, such as fuel, service, and repair costs. These variable costs are the primary factor determining the project's net profit.

- Fuel Consumption (Fc)

The measurement of fuel consumption is complex. Therefore, fuel consumption is approximated using data from the equipment manufacturer. The manufacturer provides the owner with a handbook that includes the fuel consumption for each machine, based on the machine size, engine load factor, and engine fuel consumption [35]. Fuel consumption increases in proportion with machine speed. Therefore, the higher the speed at which the machine is operated, the greater the amount of fuel used.

Fuel consumption can be reduced by operating the machine at a slower speed. However, that machine will then take more time to complete its task. As a result, the time of other machines might be wasted, as they wait for the first machine to finish its job. This will increase the overall pollutant emissions. The mathematical model should decrease fuel consumption and pollutant emissions of all the equipment used during construction.

The United States imports 45% of its fuel. The cost of this importation in 2014 was about 460 million dollars. In addition to the economic impact, the environmental (climate change) impact is significant. About 21 lb of CO_2 is produced by burning one gallon of gas [36].

- Percentage of Service Cost (Psc)

Service cost (i.e., standard maintenance) is related to the oil, grease, hydraulic fluids, filter cost and the labour needed to complete all these services. Machine manufacturers issue data that considers all these services to determine each machine's service cost under different conditions that represent the severity of the operating conditions. The standard method uses fuel consumption and the severity of the working conditions to compute the service cost. [34].

- Repair Cost (Rc)

The customer and the machine manufacturer control many significant variables determining repair costs. These variables determine the total price for repair per hour, based on the customer requirements and/or the equipment condition. Repair costs depend upon how the machine is used, its age, and preventive maintenance. It has been noticed that the repair cost is significant for determining the operating cost for a construction project [34].

(3) Contract Description

The equipment speciation represents all items that will be factored in planning the project are written into the contract to provide the contractor with all the data that might influence the cost and time calculations. These items are used in our framework to get optimal results. They are divided into three main categories: total project quantity, swell factor, and project time and cost.

- Total Project Quantity (Tpq)

This item will be available in the contract using the unit of cubic bank meters (CBM). However, during the first step, our framework will convert the unit of (CBM) to the unit of loose cubic meters (LCM) via swell factor [37].

- Swell Factor (Sf)

During the excavation process, air void space is introduced into the soil that is exhumed. The Swell Factor is defined as the unit of soil volume in the bank, which is more than the soil volume unit in the bank status [37].

- Project Time (Pt) and Project Cost (Pc)

This item is extracted from the contract to identify the time and the cost allowed to finish the project. Time and price are competing objectives in the construction project's planning, and both are dependent on diverse parameters. Because of this, managers often have difficulty finding the optimal tradeoff between these two objectives in a construction project [5].

(4) Equipment Speciation

The equipment speciation represents all specifications related to the equipment used in the proposed model. These specifications are written in the machine manufacturer's handbook to give contractors all the needed variables to predict work progress. Many factors are used to obtain the results. They are divided into four main categories: safety speed of equipment, essential cycle time, bucket fill factor for loader, and dump time of the Truck.

- Truck Safety Speed ($\bar{E}s$)

Safety is considered a constraint on the optimization process. Earthmoving equipment is associated with higher risks than any other construction equipment. Earthmoving equipment speed increases these risks and is regarded as a top priority in this model. There are many types of risks associated with earthmoving equipment speed. First, the operator might fall from the equipment. This type of risk increases exponentially with higher speeds. Second, equipment that collides with other equipment or with the fixed objects at the site can cause more damage if the speeds are higher. Therefore, the model is designed to not allow the use of speeds more than the safe speed at any time during the optimization process.

- Basic Cycle Time for Excavator (Tct)

Basic cycle time is specified in the manufacturer's handbook. The user can get the basic cycle time for each machine based on the job condition and the equipment size. (Small equipment has shorter cycle times than large equipment). Machines will have a shorter cycle with ideal job conditions [31].

- Bucket Fill Factor for Excavator (Bff)

Many valuable tables help the user obtain the appropriate value for the bucket fill factor. By multiplying the bucket fill factor with the nominal bucket volume, the actual estimation of the bucket's material volume can be determined.

- Efficiency Factor (Ef)

The efficiency factor used in the mathematical model is determined based on two main criteria: management and job conditions. There are two main ways to express job efficiency. The first way is to know how many actual working minutes occurred per hour. This is calculated by dividing working minutes by 1 h (60 min). The second way is by multiplying the efficiency factor with the theoretical cycles per 60-min-h [31].

- Dump time of Truck (Dtt)

Dump time depends on the excavator capacity obtained from the manufacturer's handbook.

- Undercarriage Cost (Tu)

The undercarriage is part of the operation cost for a truck-type of equipment, such as an excavator. The undercarriage protects the tire from environmental damage associated with normal wear and abrasive areas. Thus, it would be calculated per hour separately. This is treated as a separate factor rather than a part of a repair cost for the equipment.

- Original Life Cycle of Tire for Truck (Ocl)

A tires' life cycle is based on many factors, such as the tire type, the nature of the project, and the equipment speed. Estimating the tire-associated costs is challenging due to many variables other than the tire cost, which is considered a vital part of the direct cost. The tire manufacturer estimates the tire life cycle under standard conditions. However, this cost might need to be changed based on the project's conditions.

3.2. Model formulation

3.2.1. Decision variables identification and selection phase

Based on the literature review results, the decision-making variables that affect the time and cost objectives were identified during this phase. Five key variables were placed, and four were discussed thoroughly in previous research without developing a precise mathematical model [4,38]. The primary variable (truck speed) was innovatively considered in deriving the proposed mathematical model.

It is vital to consider truck speed as the primary variable when deriving the mathematical model. The models' complexity is expected to be amplified after considering such a primary variable. Such a conclusion is supported by the fact that this feature is expected to minimize the time and cost objectives significantly. Also, this variable is expected to increase the fuel consumption as this item is a function of truck speed. Therefore, more fuel will be consumed to meet the engine revolution requirements when the Truck moves at higher speeds.

In contrast, if the Truck moves at a slower speed, more time will be required to achieve the intended goal, yet more fuel will be saved. Also, even though the time would be saved during higher speeds, the queue will be made at a certain point due to the machines moving at high speed, and all machines will be stopped to wait for the production line to operate. Moreover, one of the main factors determining the tires' life cycle is equipment speed, where high speed reduces the tire's life cycle and thus increases the overall cost.

The following design variables were chosen: (1) The number of excavators, (2) The number of trucks, (3) The capacity of excavators, (4) The capacity of the trucks, and (5) The speed of the trucks. Table 1 shows these five design variables (along with their notations), used to formulate the mathematical optimization model for earthmoving activities.

Table 1 Description of design variables.

Decision variables	Notation	Description
Number of excavators	Nle	Has a maximum to avoid the delay due to a queue of trucks
Number of trucks	NTP	Depends on the maximum number of excavators
Capacity of Excavator	Ec	Can be determined from the manufacturer handbook (m3)
Capacity of Truck	Tip	Can be determined from the manufacturer handbook (m3)
Speed of Truck	Es	Has minimum and maximum values based on the DOT requirements and the manufacturer handbook (km/h)

3.2.2. Constraints identification phase

The mathematical model permits the user to assign various constraints related to equipment availability and speed to avoid delays due to equipment queues. Table 2 shows the upper and lower limit for these primary optimization constraints.

3.2.3. Objectives Formulation phase

This mathematical model's primary objective functions are to (1) minimize the project time and (2) minimize the associated cost. The model derives the project time and cost from all the decision-making variables. The mathematical model is described in the following sections.

(1) Equipment Direct Cost

The total cost of owning and operating each piece of equipment is calculated with Eq. (1).

$$TotalOwingCost = Ch + Ic + In + Pt(\$/hr) \quad (1)$$

Where Ch represents the equipment cost per hour as shown in Eq. (2), Ic equals the interest cost based on Eq. (3), In represents the insurance cost (in dollars per hour) as shown in Eq. (4), and Pt represents the tax cost given by the law presented in Eq. (5).

$$EquipmentCostPerHour(Ch) = \frac{Nt}{H}(\$/hr) \quad (2)$$

$$InterestCost(Ic) = \frac{P(N+1) + Rvr(N-1)}{2 \times H} \times Sr(\$/hr) \quad (3)$$

$$InsuranceCost(In) = \frac{P(N+1) + Rvr(N-1)}{2 \times H} * Ir(\$/hr) \quad (4)$$

$$TaxCost(Pt) = \frac{P(N+1) + Rvr(N-1)}{2 \times H} \times Tr(\$/hr) \quad (5)$$

Table 2 Mathematical model constraints.

Constraints		Lower limit	Upper limit
Equipment availability	Capacity	Assigned by user	Assigned by user
	Number	Assigned by user	Assigned by user and optimization equation
Equipment speed	Truck speed	Manufacturer handbook	Manufacturer handbook and State laws

where Nt (Net Value) is the Delivered Price (P) minus the Less Residual Value at Replacement (Rvr) in dollars, H is the Ownership Usage in hours, N is the Estimated Ownership Period (hours), Sr is the Simple Interest Rate, Ir is the Insurance Rate, and Tr is the Tax Rate.

The total operating cost can be written as shown in Eq. (6).

$$TotalOperatingCosts = Rc + Ow + Add + Tu + Cf + Sc + Rp(\$) \quad (6)$$

where Rc is the Repairing Cost in dollars per hour, Ow is the Operator Wage in dollars per hour, Add is the Additional Cost in dollars per hour, Tu is the Undercarriage Cost as shown in Eq. (7), Cf is the Cost of Fuel per hour, as addressed in Eqs. (8a, 8b), Sc is the Service Cost as presented in Eq. (9), and Rp is the Replacement Cost of Tire as shown in Eqs. (10a, 10b).

$$Tu = (Ui + Ua + Uf) \times Bf(/hr) \quad (7)$$

Where Ui is the Undercarriage (Impact), Ua is the Undercarriage (Abrasiveness), Uf is the undercarriage, Bf is the Basic Factor. In the case of truck equipment, this term is zero.

(2) Fuel Consumption Calculations

The fuel consumption for the Excavator is computed using two factors (1) the Unit Price for fuel, which is based on user input, and (2) Fuel Consumption per hour obtained from the equipment manufacturer's handbook. The fuel cost will be computed for the Excavator regardless of its speed because Excavator speed has a trivial impact on its fuel consumption due to the short distances, as shown in Eq. (8a)

$$ExcavatorCostFuel(Cfe) = Fce \times Up(\$/hr) \quad (8)$$

Where Fce is the Fuel Consumption of Excavator (liters) per hour and Up is the Unit Price for fuel (dollars).

The truck fuel cost is calculated using three factors (1) the Unit Price for fuel, which is determined based on the state, (2) the Fuel Consumption per hour, which is obtained from the equipment manufacturer's handbook; and (3) the Truck speed which has a substantial impact on the fuel consumption, due to the long distances. The truck fuel cost is shown in Eq. (8b).

$$TruckCostFuel(Cft) = (Fct + X \times Es) \times Up(\$/hr) \quad (8b)$$

where Fct is the fuel consumption of truck (liters) per hour, Es is the truck speed (km/h) and the decision-making variable, X is a linear correction factor of fuel consumption that varies, based on user input.

(3) Service Cost Calculations

The service cost is based on operating conditions and fuel consumption, which vary with truck equipment time. The service cost factor is tabulated in Table 3 to calculate the effect of the operating conditions [31]. The total service cost is then calculated as shown in Eq. (9).

$$\text{TotalServiceCost(Sc)} = Equipmentcostfuel \times Servicecostfactor(Psc)(\$/\text{hr}) \quad (9)$$

The total service cost of the Truck is divided into two types (1) fixed service cost as expressed in Eq. (9a), and (2) variable service cost as expressed in Eq. (9b). In the case of an Excavator, the service cost is considered as a fixed service cost only.

Table 3 Service cost factors.

Operating Conditions	Service Cost Factor
Favorable	0.20
Average	0.33
Severe	0.50

$$\text{FixedServiceCostofTruck(FSc)} = FCft \times Psc(\$/\text{hr}) \quad (9a)$$

$$\text{VariableServiceCostofTruck(VSc)} = VCft \times Psc(\$/\text{hr}) \quad (9b)$$

(4) Replacement Tires Cost Calculations

Calculation of the tire's modified life cycle in Truck hours uses the calculated cost of replacing a set of tires for the Truck. Replacement tire costs are computed based on the (1) tire price, (2) tire lifetime, and (3) truck speed. Truck speed has a significant impact on the replacement cost of tires due to the long distance [31]. The modified life cycle of tires and the replacement tire cost is calculated as shown in Eq. (10).

$$ReplacementCostofTire(Rp) = \frac{Rct}{(1.24 - 0.01 \times Es) \times Ocl} \times (\$/hr) \quad (10)$$

where Ocl is the original life cycle of the tire (in hours) for Truck, and Rct is the Replacement Cost of a set of tires. (In the case of tracked excavator equipment, this last term is zero.)

The direct cost is divided into a fixed cost and a variable cost. The direct excavator cost is expressed only in terms of a fixed cost. Due to the lack of a speed-dependent cost, no variable excavator cost is considered. The fixed excavator cost is computed based on owning and operating costs, as shown in Eq. (11). On the other hand, the truck cost is categorized into two types of costs, (1) fixed cost, which includes equipment cost, interest cost, insurance cost, tax cost, repairing cost, and operator wage, and (2) variable cost, which includes the fuel, tires, and service costs, as shown in Eqs. (12) and (13) respectively.

$$Directexcavatorcost(B) = Ch + Ic + In + Pt + Rc + Ow + Tu + Cfe + Sc + Add(\$/hr) \quad (11)$$

$$Fixedtruckcost(A) = Ch + Ic + In + Pt + Rc + Ow + Add + FCft + FSc(\$/hr) \quad (12)$$

$$Variabletruckcost(C) = VCft + VSc + Rp(\$/hr) \quad (13)$$

The direct truck cost is based on Eqs. (12 and 13). This cost can be formulated as shown in Eq. (14).

$$\text{DirectTruckcost} = \frac{(1.15 \times \text{A} \times \text{Ocl} + \text{Rct}) + \text{Ocl} \times (1.15 \times \text{X} \times (\text{W}) - 0.01 \times \text{A})\text{Es} - 0.01 \times \text{X} \times \text{Ocl} \times (\text{W}) \times \text{Es}^2}{\text{Ocl}(1.15 - 0.01 \times \text{Es})} (/\text{hr}) \quad (14)$$

Where W is a constant calculated by Eq. (14a).

$$W = (Up + Psc \times UP) \quad (14a)$$

The next step in the objective's derivation is to represent the equipment productivity mathematically. The excavator productivity is calculated as shown in Eq. (15).

$$Excavatorproductivity(Ep) = \frac{Nle \times Ec \times Bff \times Ef \times 60}{Tct} \times (m^3/hr) \quad (15)$$

Where Nle is the number of excavators, which is a decision-making variable, Ec is the excavator capacity (in cubic meters) which is a decision-making variable, Bff is the bucket fill factor, Ef is the efficiency factor, and Tct is the total cycle time (in s).

An essential operation during earthmoving activity is to transfer the soil from the excavation area to a specific dumping area. The time required for this step is calculated via Eq. (16).

$$TotalcycletimeforTruck(Tctt) = Dtt + Tt + Ldt(minutes) \quad (16)$$

Where Dtt is the dumping time of Truck, obtained from the equipment manufacturer's handbook based on the truck type, Tt is the travel time of Truck, as shown in Eq. (17), and Ldt is the Loading Time of Truck as shown in Eq. (18).

$$TravelTime(Tt) = \frac{60 \times Md}{Es}(minutes) \quad (17)$$

Where Md is the doubled distance between the dumping area and construction site (km).

The Truck loading time at the work site differs with the number and capacity of the Excavator. For instance, increased excavation operation would result in a shorter truck loading time. The type and number of excavators need to be optimized to minimize the time and cost objective functions.

$$LoadingTimeofTruck(Ldt) = \frac{Tic \times Tct}{Nle \times Ec \times Bff \times Ef} \times (minutes) \quad (18)$$

Where Tic is the truck capacity (in cubic meters) which is a decision-making variable.

To represent the loading truck time equation in a suitable form, it can be rearranged as shown in Eq. (18a).

$$LoadingTimeofTruck(Ldt) = \frac{Nol \times Tct}{Nle}(minutes) \quad (18a)$$

Where Nol is the number of loads defined as $(Tic \times Tct/Ec \times Bff \times Ef)$.

When the previously presented equations are combined and rearranged, the mathematical formulas for the time and cost objectives are shown in Eqs. (19) and (20), respectively.

$$Activitytime = \frac{Tpq \times Tct \times Es + 60 \times Md \times Ec \times Bff \times Ef \times Nle}{60 \times Ec \times Bff \times Ef \times Es \times Nle} \times (hr) \quad (19)$$

Eq. (19) can be rewritten in a more straightforward form, as shown in Eq. (19a).

$$ActivityTime = \frac{c1 \times Es + c2 \times Nle}{c3 \times Es \times Nle}(hr) \quad (19a)$$

where c1, c2, and c3 are constants computed based on the user inputs, as shown below:

- $c1 = Tpq \times Tct$
- $c2 = 60 \times Md \times Ec \times Bff \times Ef$
- $c3 = 60 \times Ec \times Bff \times Ef$

$$Activitycost = activitytime \times ((Numberofexcavators \times totalcostofexcavator) + (NumberofTrucks \times Totalcostoftruck))$$
$$= \frac{[a1 \times Nle + a2 \times Es + a3 \times Nle \times Es + a4 \times Nle \times Es^2 + a5 \times Es^2 + a6 \times Es^3 + a7 \times Nle \times Es^3]}{b1 \times Nle \times Es + b2 \times Nle \times Es^2}() \quad (20)$$

Where a1, a2, a3, a4, a5, a6, a7, b1, and b2 are constants calculated based on user inputs, as shown below:

- $a1 = Tpq \times Tct \times (60 \times Md(1.24 \times A \times Ocl + Rct)$
- $a2 = Tpq \times Tct \times Nol(1.24 \times A \times Ocl + Rct)$.
- $a3 = Tpq \times Tct \times (60 \times Md \times Ocl(1.24 \times X \times W - 0.01 \times A) + Rct \times Dtt + 1.15 \times B \times Ocl \times Nol + 1.24 \times A \times Ocl \times Dtt)$
- $a4 = Tpq \times Tct \times (Dtt \times Ocl(1.24 \times 0.12 \times W - 0.01 \times A) - 0.01 \times X \times 60 \times Ocl \times W \times Md - 0.01 \times B \times Ocl \times Nol)$
- $a5 = Tpq \times Tct \times Nol \times Ocl(1.24 \times X \times W - 0.01 \times A)$
- $a6 = -Tpq \times Tct \times (0.01 \times X \times Ocl \times W \times Nol)$
- $a7 = -Tpq \times Tct \times (0.01 \times X \times Ocl \times W \times Dtt)$
- $b1 = 1.24 \times 60 \times Ec \times Bff \times Ef \times Ocl \times Nol$
- $b2 = -0.01 \times 60 \times Ec \times Bff \times Ef \times Ocl \times Nol$

To move forward towards the optimization phase, these time and cost objectives are reformulated to meet the GA optimization technique's requirements, as shown in Eqs. (21) and (22).

$$ActivityTime(AT) = \frac{\sum_{k=0}^{1}\sum_{q=0}^{1} c(k,q) \times Nle^k \times Es^q}{\sum_{k=0}^{1}\sum_{q=0}^{1} c(k,q) \times Nle^k \times Es^q} \times (hr) \quad (21)$$

$c(o,o) = 0, c(o,1) = c1, c(1,0) = c2, and c(1,1) = c3$

$$ActivityCost(AC) = \frac{\sum_{k=0}^{1}\sum_{q=0}^{3} a(k,q) \times Nle^k \times Es^q}{\sum_{k=0}^{1}\sum_{q=0}^{2} b(k,q) \times Nle^k \times Es^q}(\$) \quad (22)$$

$a(o,o) = 0, a(1,0) = a1, a(0,1) = a2, a(1,1) = a3,$
$a(1,2) = a4, a(0,2) = a5, a(0,3) = a6, a(1,3) = a7,$
$b(o,o) = b(0,1) = b(0,2) = 0, b(1,1) = b1, and\ b(1,2) = b2.$

3.2.4. Model Implementation phase

The GA calculations in the mathematical model are categorized into four primary phases: (1) the data input phase for all related constants and parameters (which also includes the primary optimization constraints) to generate an initial population of random variable sets for the optimization problem, (2) the calculation of the time and cost for each set of random variables within the initial population; (3) the assessment of the fitness of each set of random variables, using a defined evaluation method and the objective functions; and (4) the use of mutation and crossover processes and the evaluation of the many alternatives. This procedure is repeated until the optimum set of variables is found within the applied constraints [25]. Flowchart of the adapted algorithm is shown in Fig. 2.

The mathematical model must be applicable for a wide range of real applications. Therefore, it allows the user to specify values for all the constants while taking into consideration (1) the minimum and maximum boundaries for the model's decision parameters, which include the number of trucks, the capacity of the trucks, the speed of the trucks, the number of loaders, the capacity of the loaders (as provided in Table 3) and (2) the mathematical model inputs such as total project quantity (m^3), the bucket fills factor for Excavator, efficiency factor, percentage of Service cost, moving distance (km), machine designation, direct cost ($/h), the unit price for fuel ($/ liter), fuel consumption per hour, excavator capacity (m^3), truck capacity (m^3), the replacement cost of the tires ($), the life cycle of the tire (hr), and the Max speed (km/h) as shown in Tables 4 and 5.

3.3. Testing and validation

An earthmoving project during a public school construction was employed to test and validate the proposed model. This demonstrated the model's application and competencies in creating optimal sets of tradeoffs between time and cost objectives. The total excavation of the 9730-meter cube (loose) material project was sponsored by the USAID program, which requires dumping the excavated soil materials into a specified area that is 5.5 km away from the construction site. A class I construction company was responsible for the excavation and dumping (earthmoving) activities. Two CAT 320D2 excavators were used for excavation activities, while two CAT 725C and CAT 735C trucks were used to transfer the soil to the dumping place. The excavated material type was sand, and gravel based on soil tests, which yields an excavator

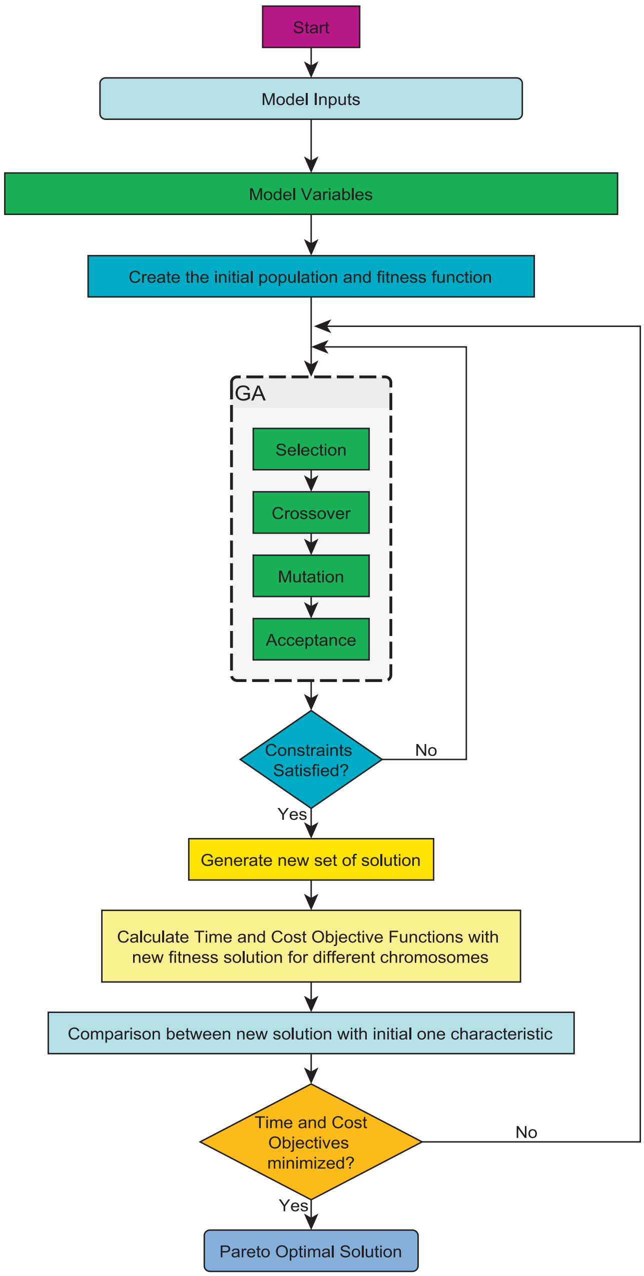

Fig. 2 Flowchart of adopted optimization algorithm.

bucket fill factor of 0.95. Job and management conditions were categorized as GOOD with an efficiency factor of 0.75. Average operating conditions were reported, and the service cost was 33% of the total project cost. Table 4 summarizes the input data related to the project and contract conditions.

The contractor estimated the fixed direct cost per hour to be 45, 44, and 53 for the 320D2 Excavator, 725C, and 735C Truck. This cost includes equipment cost, the interest cost, insurance cost, tax cost, repairing cost, and operator wage. The average price for diesel fuel per liter is 1.1 USD. The fuel consumption has been recorded for the 320D2 Excavator, 725C, and 735C Truck as 21, 23, and 28 USD, respectively, which complies with the average fuel consumption ranges in the CAT equipment handbook. According to the CAT equipment handbook, the 320D2 Excavator, 725C, and 735C truck capacity are 0.9, 15, and 20.5 cubic meters, respectively. For the Truck, rubber tires must be replaced after certain operational hours. According to the tire manufacturer, the tire life cycle was 3,000 h of operation. However, this lifecycle is subject to a change based on the equipment speed. The mathematical model considers the effect of speed in altering the tire life cycle. The tire replacement cost is 3,000 USD and 3,300 USD for all the tires for 725C and 735C trucks, respectively. As reported in the CAT equipment handbook, the maximum speed for 725C and 735C trucks is 54 km per hour. Data related to construction equipment is shown in Table 5. According to the contractor file report, the Truck was operated at its maximum speed, and the total project cost and duration were 29,000 USD and 90 h.

Table 4 Data related to project and contract conditions.

Input Data	Notation	Value
Total Project quantity (m^3)	Tpq	9,730.45
The bucket fill factor for Excavator	Bff	0.95
Percentage of Service Cost	Psc	33%
Moving Distance (Km)	Md	11 km

4. Results and discussion

4.1. Cost time optimal tradeoffs

The developed mathematical model was set to optimize the cost and time for this case study to recognize optimal tradeoffs between minimizing these objectives, as shown in Fig. 3. The optimized set contains various optimal solutions, from which the contractor can choose according to the project's circumstances (e.g., time and cost sensitivity). This model created an optimal set for every combination of equipment (e.g., where 1 excavator and 2 trucks were used, there are 2 equipment combinations). Each of the generated optimal tradeoffs shown in Fig. 3 (320D2 excavator and 725C Truck equipment) can be obtained by executing an optimal combination of project and equipment parameters for the first combination. Fig. 4 represents the optimal tradeoff for the second combination (320D2 Excavator and 735C Truck equipment).

The created tradeoffs provide the user with various optimized solutions, as shown in Fig. 3. For instance, solution A represents the optimal solution with a minimum time of 51.74 h and a maximum cost of 32,678.0 USD, while solution C represents the optimal solution of a full time (152.19 h) and a minimum cost (26,416.4 USD). Solution A was created using three 320D2 excavators and four 725C trucks with 38 km/h. Solution C was generated using one 320D2 Excavator and two 725C trucks with a 45 km/h speed. Implementation of solution A will save 38.26 h (a 42.5% timesaving) of the project duration, with a cost increase of 3,678 USD (12.7% extra cost). Solution A provides significant time savings with a slight cost increase. Solution C will reduce the total cost by 2,583.6 USD (an 8.9% saving), while the time will be increased by 69.1% (an extra 62.19 h). To reduce both time and cost objectives, solution B could be adopted. This solution was created with two 320D2 excavators and three 725C trucks with 42 km/h to reduce the cost by 561 USD (2% cost saving) and a reduction of 12.84 h (14.3% timesaving).

Table 5 User-specified equipment input data.

Input Data	Notation	Excavator	Truck 1	Truck 2
Machine Designation	type	320D2	725C	735C
Direct Cost ($/h)	DC	45	44	53
Unit Price for fuel ($/ liter)	Up	1.1	1.1	1.1
Fuel Consumption per hour	Fct	–	23	28
Fuel Consumption per hour	Fce	21	–	–
Excavator Capacity (m^3)	Lc	0.9	–	–
Truck Capacity (m^3)	Tic	–	15	20.5
Replacement Cost of Tire ($)	Rct	–	3,000	3,300
The original Life cycle of Tire (hr)	OLc	–	3,000	3,000
Max speed (km/h)	Ms	–	54	54

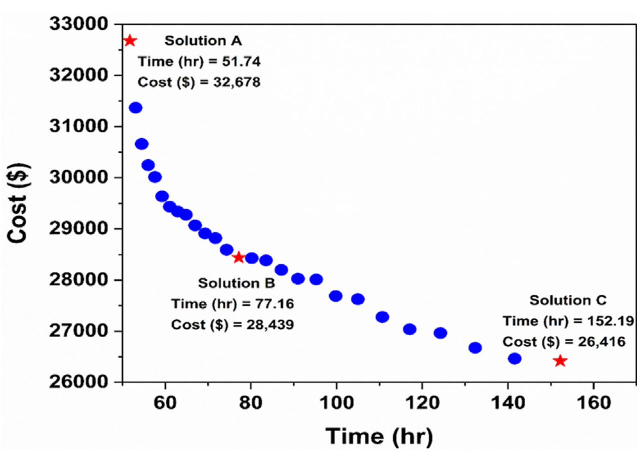

Fig. 3 Optimal trade-offs for combination 1 (320D2 and 725C).

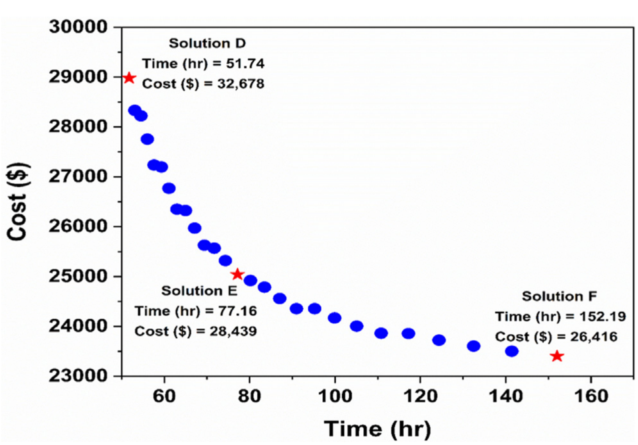

Fig. 4 Optimal trade-offs for combination 2 (320D2 and 735C).

The created tradeoffs provide the user with various optimized solutions, as shown in Fig. 4. For instance, solution D represents the optimal solution with a minimum optimized time of 51.74 h and a maximum optimized cost of 28980.9 USD, while solution E represents the optimal solution of a maximum time (152.04 h) and a minimum cost (23,403.05 USD). Solution D was created using three 320D2 excavators and three 735C trucks with 40 km/h. On the other hand, solution F was generated using one 320D2 Excavator and two 725C trucks with 42 km/h. Implementation of solution D will save 38.26 h (42.5% timesaving) of the project duration and almost with the same cost of the earthmoving activity. Solution D provides significant timesaving. Solution F will reduce the cost by 5,596.95 USD (a 19.3% saving), while the time will be increased by 68.9% (an extra 60.04 h). To implement a time and cost-saving solution, solution E could be adopted. This solution was created using two 320D2 excavators and three 725C trucks with a speed of 39 km/h, saving 3,957.9 USD (a 13.6% cost saving) and 12.87 h (a 14.3% timesaving). Selected optimal solutions are summarized in Table 6.

The optimal tradeoffs created by the mathematical model provide decision-makers with a tool to select an optimal solution for time and cost minimization during earthmoving activities based on the project's circumstances. These optimization results indicate that the optimal combination's appropriate equipment selection plays a critical role in the time and cost savings, as shown in Fig. 5. Contractors and construction management engineers can evaluate these optimal tradeoffs to determine the minimum possible time and cost for a given set of equipment types, equipment numbers, and equipment speeds.

The developed model generates Time-Cost Pareto tradeoffs, which are generic and provide various solutions. Thus, solutions B and E were chosen to provide optimal tradeoffs (lower time with reasonable cost). It is worth mentioning that all developed solutions are optimal and can be selected based on different site circumstances and equipment's characteristics. Consequently, these two solutions, B and E, were chosen for illustration purposes only. The presented model validation (i.e., the case study) was utilized only to show how the models operate, where key inputs and outputs are highlighted and discussed. For example, the mathematical model uses variables for any arbitrary location and various types of equipment (e.g., Excavator and Truck). When the location conditions or equipment's characteristics are changed, the model's inputs will also change, generating new results. In summary, the developed optimal solutions allow the users to choose the solution that fits the current circumstances of the project based on a comprehensive comparison. Thus, the decision-making process is expected to be thoroughly enhanced.

4.2. Environmental impact assessment

According to Environmental Protection Agency (EPA), about 15 million pounds of CO_2 emissions will be reduced (around

Table 6 Optimal time and cost Sample Solutions summary.

Design Variable	Combination 1 (320D2 and 725C)			Combination 2 (320D2 and 735C)			Equipment Combination
	Solution A	**Solution B**	**Solution C**	**Solution D**	**Solution E**	**Solution F**	
NTP	4	3	2	3	3	2	2 of CAT 725C2 of CAT 735C
Nle	3	2	1	3	2	1	2 of CAT 320D2
Tip (m^3)	15	15	15	20.5	20.5	20.5	15 of CAT 725C20.5 of CAT 735C
Ec (m^3)	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Es (km/h)	38	42	45	40	39	42	54
AT (hr)	51.74	77.16	152.19	51.74	77.13	152.04	90
AC ($)	32,678.0	28,439.0	26,416.4	28,980.9	25,042.1	23,493.05	29,000

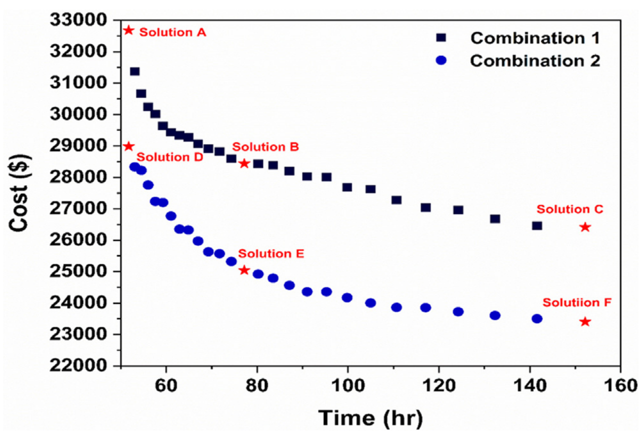

Fig. 5 Optimal combinations.

5% of the total CO_2 emissions) when diesel fuel consumption decreases by 10% in construction projects [39]. The primary source of air pollution in construction projects is the equipment that uses diesel fuel to power their engines [40]. Also, these engines are directly related to several types of environmental pollution (e.g., nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC). Such emissions from construction projects contributed about 38% of the total emissions in 2019 [41]. Activities that cause the emission of these pollutants must be controlled during construction projects. It has been estimated that the excess consumption of diesel fuel from trucks due to mismanagement is almost 960 million gallons during construction projects. About 5.55 lb of CO_2 is produced by burning each gallon of gas [36]. Due to greenhouse gas emissions (GHG), the global temperature in 2100 is foreseen to rise to 2–4 °C [42]. The construction industry is considered one of the primary air pollutants and greenhouse gases, such as CO2 emissions. This sector represents one of the three major industry sectors that significantly release greenhouse gas in the US [39]. In addition to the day-by-day impacts of such a sector on the environment, construction equipment must reduce these emissions to prevent future environmental destruction. Construction equipment is a significant contributor to CO_2 emissions worldwide [43]. Construction projects need methods for decreasing fuel consumption, which negatively impacts the environment, economy, and energy conservation. Emissions from earthmoving equipment are estimated based on Activity time, Load factor, and Engine power. It can also be expressed in (kg/h) as shown in Eq. (23) [44].

$$CO_2 Emission = \mathrm{EFE} \times \mathrm{AT} \times \mathrm{LFE} \times \mathrm{EPE}. \quad (23)$$

Where EFE is the Emission factor of $CO_2(g/hp - hr)$, AT is the Activity time for earthmoving equipment (hr), LFE is the Load factor for earthmoving equipment, and EPE: is the Engine power for the earthmoving equipment (hp).

CO_2 emissions can be computed using Eq. (24).

$$CO_2 Emission = \frac{EFE \times LFE \times EPE \times \sum_{k=0}^{1}\sum_{q=0}^{1} c(k,q) \times Nle^k \times Es^q}{\sum_{k=0}^{1}\sum_{q=0}^{1} c(k,q) \times Nle^k \times Es^q} \quad (24)$$

The emission factor characterizes the emitted pollutant while the equipment is on. It represents the ‘‘unit emissions” when the equipment is idling or running [40]. The average value for this factor is 550 g/hp-h for the CO_2 pollutant [42]. Activity time represents how many hours are needed for the earthmoving equipment to fully complete the activity, including the delays, as the equipment is kept on. Load factor estimates this value for the construction project's equipment, as a load factor of 1 (100%) is unrealistic. The Load factor can be represented as a percentage of the total power for earthmoving equipment within the construction site. The equipment's engines are run with several loads and speeds, and are rarely applied at planned conditions [44]. This factor reflects the usual situation with the actual site conditions (limited load conditions, transient operation, and delays). This factor is obtained from the manufacturer's equipment handbook and annual reports released from the EPA. To be conservative, the load factor based on EPA data is taken to be 0.5. Engine power (horsepower of the equipment used in the Equation) is the average engine power based on the size and type of equipment engine. Also, this value is obtained from the manufacturer's handbook or data from the EPA. The mathematical optimization model helps reduce pollutant emissions for each piece of equipment. For example, the CO2 emission reduction in optimum solution A was 21,289 kg. This shows the model's potential for reducing the adverse effects on the environment. Table 7 is used to calculate the CO_2 emission for all the previously discussed optimal solutions. Table 8 shows that the CO_2 emission is significantly reduced from the baseline for all selected optimal solutions.

4.3. Sensitivity analysis

To fully understand the effect of each variable on the time and cost objective functions, it is helpful to conduct a comprehensive sensitivity analysis. In addition, sensitivity analysis helps a decision-maker understand the model's behavior concerning

Table 7 Equipment details used for the earthmoving activity.

Equipment Type	Model	Model Year	Engine Power (hp)
Excavator	CAT 320D2	2008	146
Truck	CAT 725C	2010	329
	CAT 735C	2011	452

Table 8 CO_2 Emission comparison.

Scenarios	Selected Solutions	Operating time (hr)	CO_2 emission (kg)
Baseline	–	90	45,887
Combination1	A	51.74	24,598
	B	77.16	27,140
	C	152.19	33,651
Combination 2	D	51.74	25,526
	E	77.13	34,955
	F	152.04	43,902

several variables. To address the sensitivity of the primary objectives (i.e., time and cost) to changes in excavator number, all other variables can be assigned a fixed value (e.g., Truck speed is 45 km/h and the number of Trucks is two) while the number of excavators can be varied from 1 to 7. The result of that analysis is shown in Fig. 6.

The effect of changing the number of trucks can also be investigated. All other variables can be assigned a fixed value (e.g., Truck speed is 42 km/h and the number of excavators is 3) while the number of trucks varies from 1 to 10. The result of the analysis is shown in Fig. 7.

This analysis represents the effect of Excavator and Truck number variables on both study objectives. As the number of excavators increases, the associated costs increase linearly, reflecting the non-linear and non-convex nature of the cost objective function. The same observation for the change in the number of trucks can be seen. The time decreases nonlinearly as the number of excavators increases. As the number of excavators goes beyond four, the time function becomes constant, as it is ineffective to have more than 4 excavators.

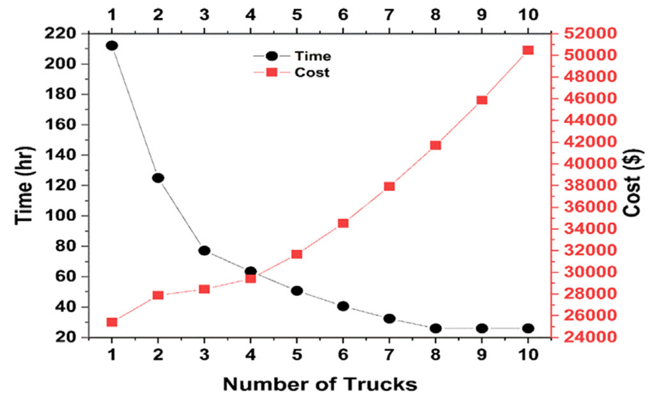

Fig. 7 Sensitivity analysis-truck number.

The same behavior can be tracked as the number of trucks changes. When the number of trucks exceeds 8, the time objective becomes constant. This is due to the queueing and idling of the trucks. The number of excavators and the number of trucks affect the cost, as it is based on the number of hours when the equipment is reserved, even if they are not operating. The number of excavators has a higher impact on the cost objective.

On the other hand, the time objective function is affected only slightly as the number of trucks or excavators is altered. It is also possible to examine the objective functions as the truck speed changes. Fig. 8 shows the sensitivity analysis for time and cost objective functions as the truck speed changes and all other variables remain constant (e.g., when the number of Excavators and Trucks are each 3).

Fig. 8 shows that the cost objective function initially drops with increases in the truck speed. This continues up to a specific optimal speed point where the equipment fuel consumption increases and a truck queue appears (i.e., at a truck speed of 38 km/h). Beyond this point, the cost objective function increases tremendously as the consumed fuel increases and the queueing delay times becomes longer. This reinforces the study's primary findings, which state that the equipment speed considerably affects the cost. On the other hand, the analysis shows that the time objective function decreases as the truck speed increases. This continues up to a specific optimal speed

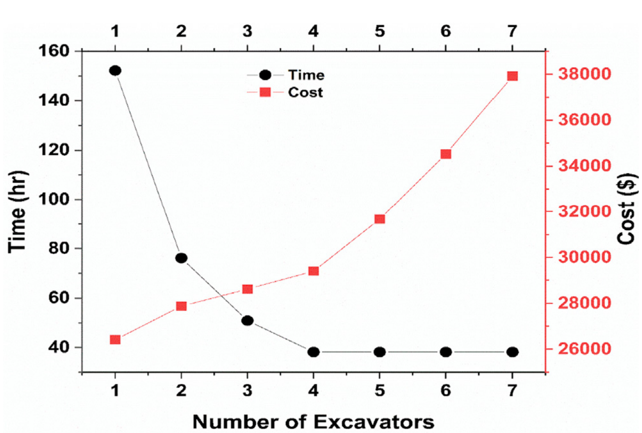

Fig. 6 Sensitivity analysis-excavator number.

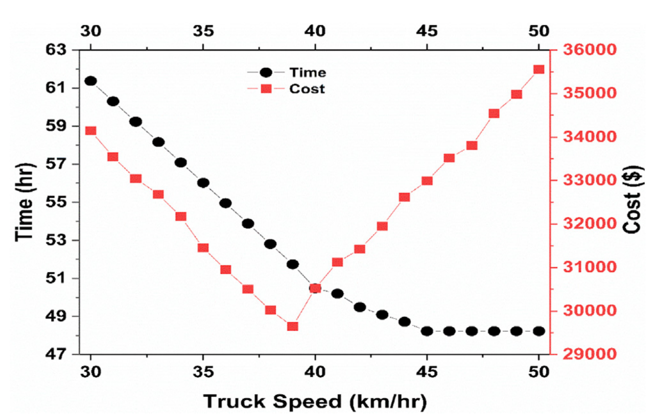

Fig. 8 Sensitivity analysis-truck Speed.

point (i.e., equipment speed of 45 km/h), where a truck queue starts to form. Beyond this point, the time objective function remains constant up to the maximum allowable speed.

5. Conclusion

This work proposed to answer the following research question:

Q: How could we use a genetic algorithm to perform multi-objective optimization to select heavy equipment in construction projects?

A: A novel multi-objective and multi-variable optimization mathematical model has been proposed to optimize the time and cost of earthmoving activities. This model was developed to optimize various decision-making variables (i.e., capacity, number, and speed). A practical field application was used to validate and evaluate the model's proficiency. The GA-based optimization results emphasize the model's ability in creating a wide variety of optimal solutions to minimize time and cost objective functions during earthmoving activities for a wide range of possible equipment combinations. For example, in equipment combination 1 (i.e., 320D2 and 725C), the provided optimization saved 14.3% and 2% for time and cost objectives, respectively, by providing a solution of using two 320D2 excavators and three 725C Trucks with the speed of 42 km/h.

Furthermore, in equipment combination 2, substantial savings in time and cost were shown. The time and cost reductions were 14.4% and 17.89%, respectively, by providing a solution using two 320D2 excavators and three 725C trucks with a speed of 39 km/h, which saved 3,957.9 USD (a 13.6% cost saving) and 12.83 h (a 14.4% timesaving). These optimization results show that appropriate equipment selection plays a critical role in time and cost savings. The optimized equipment speed (not necessarily the maximum speed) significantly reduces the activity time and provides significant reductions in fuel consumption and CO2 emissions.

The competencies of the proposed mathematical model depend upon accurate input data. The application of the model is also restricted to a single earthmoving activity. The proposed model also deals only with excavation and soil transfer from a construction site to dumping. Future research will be needed to develop the model's current capabilities further to accommodate more equipment and overcome these limitations. Also, the safety and quality objectives could be considered the main objectives and the time and cost objectives. Moreover, new multi-objective optimization algorithms can be utilized to optimize the targeted objective functions, where the optimization results for various algorithms can be compared. Furthermore, the application of new technologies (e.g., M2M, connected equipment, GPS, and GIS) could also be added.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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