

A Simulation-based Earthmoving Fleet Optimization Platform (SEFOP) for Truck/Excavator Selection in Rough Grading Project

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Abstract –

Earthmoving operations are complex system where many resources collaborate to carry out tasks. Although considerable efforts have been made in the development of efficient methods and systems for recommending appropriate fleets of equipment, in practice, average production rate method still prevails in favour of its simplicity at the cost of possible inaccuracy in planning and estimating at construction stage. In this paper, a simulation-based fleet selection methodology was introduced. Then, Simulation-based Earthmoving Fleet Optimization Platform (SEFOP), as an intuitive and efficient tool for equipment selection optimization in earthmoving operations, was presented. The proposed methodology and tool were applied on a real-world rough grading project and the outputted results proved that the SEFOP tool is able to provide a decision maker with insightful fleet selection strategy and accurate cost and duration estimates.

Keywords –

Earthmoving; Fleet Selection; Simulation; Optimization

1 Introduction

Due to the lack of specific information such as equipment models, the temporary haul road layout design, and earthworks volume assignment plans, it is unrealistic to come out with resource allocation plans by examining the detailed earthmoving operations at bidding stage. As a result, the industry often applies general deterministic approaches by applying “four to six passes” rule based on average production rates [1]. In particular, the average production rates are derived from RS Means [2] or other company-specific or industry-wide benchmarking database by considering basic factors such as fixed truck and excavator type,

bucket size, hauling distance, soil properties, average cycle time, efficiency factor, and etc. This kind of average production rates based deterministic method for fleet selection [3] is widely taught at post-secondary institutions and is the primarily applied method in construction industry. However, once being processed to the construction stage when specific field information become available, average production rates methods may fall short in resource planning and productivity estimating as it only accounts for particular categories of equipment and work conditions. As proofed by Yi and Lu in [4], the method based on average production rates tends to underestimate crew productivity by an average of 30%, compared to detailed operation analysis method, resulting in poorly selected fleet and reduced chances to the successful earthmoving operation.

In order to help obtain the optimum resource allocation in earthmoving operations, a substantial number of researches have been conducted by modelling the earthmoving operations [5][6][7]. Gransberg [8] used a deterministic method of dividing the cycle time by the loading time of the trucks in order to determine the required number of haulers. Shi [9] used neural networks in order to determine the number of haulers required for a particular excavator. Later, heuristic algorithmic innovations have been integrated with simulation modelling to optimize earthmoving operations. Marzouk and Moselhi [10] successfully established an automated system named Earth Moving Simulation Program (EMSP). It will integrate heuristic algorithms into the simulation model to select a near-optimum fleet configuration. Cheng et al. [11] proposed simulation optimization by combining GA with CYCLONE or other simulation techniques. Zhang et al. [12] further proposed an integration of particle swarm optimization (PSO) and a construction simulation so as to determine efficiently the optimal resource combination for a heavy construction operation. Integrating genetic algorithm, linear programming, and

geographic information systems (GIS). The simulation model for large-scale earthmoving operations are developed and successfully applied to two numerical examples [13]. Morley et al. [1] applied simulation to optimize truck numbers by allowing for a multiple truck and excavator types to be considered.

Nevertheless, field planners still use average production rates together with their experience by default for fleet selection at construction stage even though specific field information become available, due to the lack of professional simulation modelling and optimization training, and haste planning under time constraint. Based on author's personal research and working experience in construction industry in Alberta, field supervisors/managers are interested in simulation tools, but hesitate to apply due to prohibitive time consumption compared to average production rates method in the fast-paced and profit-chasing construction industry. In this context, it is necessary to devise a scientifically reliable yet easy-to-use tool to tap all the information at construction stage to result in a refined resource plan in guiding workforce executions to the purpose of maximizing profit.

2 Haul Job Definition

In site grading project, haul job is the fundamental unit for earthmoving planning, resource allocation, and production estimating. In this paper, a complete haul job is defined by seven attributes: source, destination, earth volume, haul path, resource, duration and cost. Varying by the earth volumes and hauling route between source and destination, the resource allocation (i.e. truck number), cost and duration for completing haul jobs could differ considerably. Generally, a source is defined by a cut area where a destination is defined by a fill area. A haul route corresponds to a pair of source and destination with a pre-planned haul path, through which the trucks pass to haul the material from cut to fill. In this thesis, haul job is further classified into two categories: cut-dominated haul job and fill-dominated haul job.

Mathematically, a haul job is defined as $H_{ij} = \{v_{ij}, P_{ij}, Res_{ij}, C_{ij}, T_{ij}\}$. v_i is the calculated soil volume in bank measure to be excavated in cut area i ; v_j is the calculated soil volume in bank measure to be dumped in fill area j ; v_{ij} is the soil volume to be hauled in current haul job. If $v_i < v_j$, H_{ij} is defined as a cut-dominated haul job; otherwise, if $v_i > v_j$, H_{ij} is defined as a fill-dominated haul job. P_{ij} is the haul path between cut area i and fill area j ; Res_{ij} is an integer number starting from 1 to indicate truck numbers allocate to current haul job; C_{ij} and T_{ij} are total cost and total duration of current haul job respectively.

In practice, the earthmoving tasks are decomposed to haul jobs to guide workforce operation executions. Similarly, in this paper, haul job serves as the fundamental unit in earthmoving fleet optimization.

3 Optimize Truck Number and Excavator/Truck Type

The number of trucks is determined in order to match up with the production rate of the excavator, which is generally assumed to be the governing resource in earthworks estimating. The number of trucks is dependent on the specific excavator being used, the specific truck type being considered, temporary haul road design, and the truck hauling cycle time. The truck selection starts with one truck. The average total haul job duration with one truck being employed will be recorded and corresponding total haul job cost will be calculated, according to Eq.(1):

$$C_{ij} = \frac{T_{avg}}{f} (U_t N_t + U_{ex} + U_{oh}) \quad (1)$$

Where T_{avg} is the average haul job duration from simulation; f is the operations efficiency factor; U_t is unit cost of truck in \$/hour; U_{ex} is unit cost of excavator in \$/hour; U_{oh} is unit cost of field overhead in \$/hour; C_{ij} is the total cost of haul job H_{ij} .

With same method, total haul job cost of employing multiple trucks can be calculated. The truck number selection strategy is illustrated in Figure 1. It is noted that the termination criterion "Cost N+1 > Cost N" means that employing one more truck will lead to total direct cost increase.

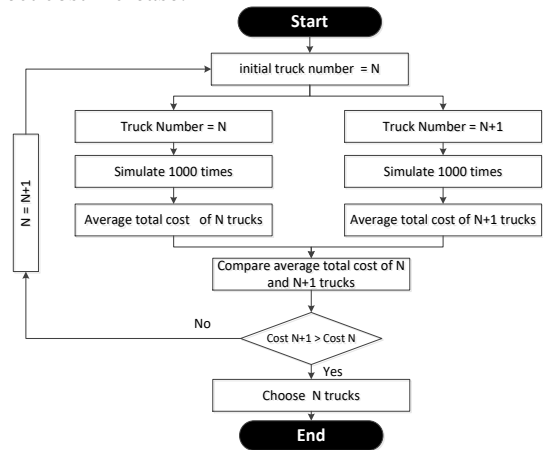


Figure 1. Simulation-based truck number optimization methodology

Having the basis of truck number optimization, truck/excavator type optimization can be made possible by adding one more loop by iterating all the possible truck/excavator combination, as shown in Figure 2. The

total project cost (consist of multiple haul jobs) under different truck/excavator combinations will be calculated and compared to result in the optimal truck/excavator selection in terms of minimum total project cost.

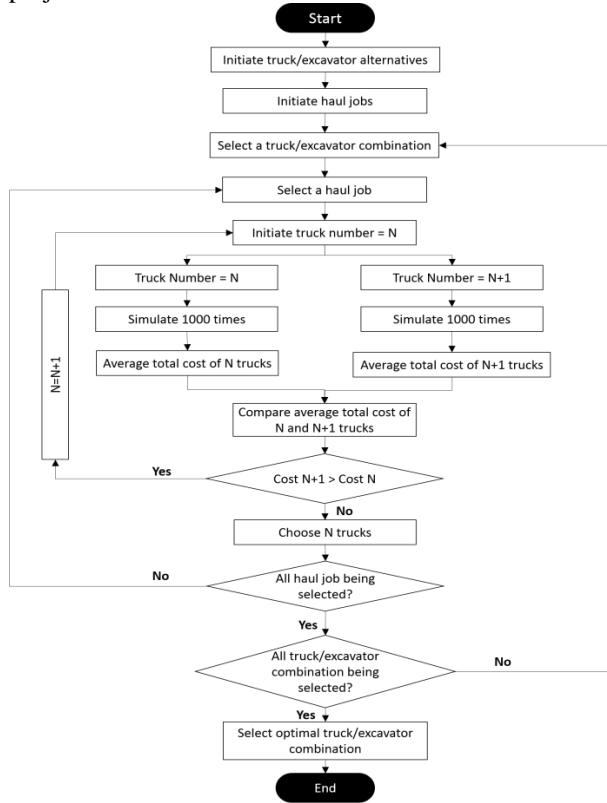


Figure 2. Simulation-based truck/excavator type optimization methodology

4 Simulation-based Earthmoving Fleet Optimization Platform (SEFOP)

For current fleet optimization problem in earthmoving operation, the whole operation process was simulated with discrete event simulation functions in SimPy, providing the foundation for the proposed Simulation-based Earthmoving Fleet Optimization Platform (SEFOP). The excavator was defined as resource in the simulation environment with a default number of 1. Truck loading, hauling, dumping and waiting was encoded with SimPy functions. When loading, the truck needs to call the excavator from resource in the simulation environment. The excavator was simulated to load the truck bucket by bucket when there is no other loading work occupied. When all the earthworks tasks done for current haul job, the program automatically outputs duration and cost, in order to identify optimal truck numbers.

Firstly, to optimize truck numbers, SEFOP will

automatically simulate haul job cost and duration under different truck numbers to identify the optimal truck numbers in terms of minimum total haul job cost. Secondly, for equipment type optimizations, SEFOP will automatically simulate different truck/excavator combinations on the basis of truck number optimization program, outputting optimal truck/excavator types together with optimal truck numbers for haul jobs. In addition, SEFOP was programmed to allow optimization for multiple haul jobs.

4.1 SEFOP Main UI Screen

By running the SEFOP application, the below User Interface (UI) will pop up for users to (1) input haul job(s) parameters, and (2) select optimization mode.

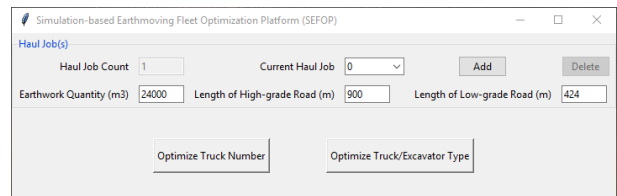


Figure 3. SEFOP User Interface (main)

For each haul job, users need to input “Earthwork Quantity (m3)”, “Length of High-grade Road (m)” and “Length of Low-grade Road (m)”. The program allows users to input multiple haul jobs by inputting haul job parameters and clicking “Add”. Users are also allowed to check each haul job being inputted by choose haul job from a dropdown menu in “Current Haul Job”, or delete any haul job by clicking “Delete”.

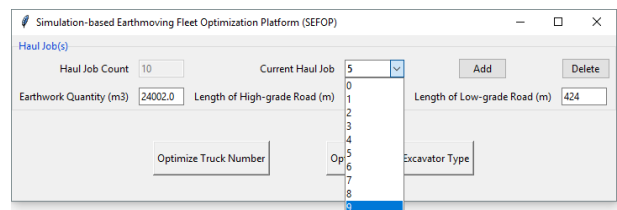


Figure 4. Add Multiple Haul jobs

Once haul job(s) information has been inputted, users can choose either to optimize truck number (when truck and excavator type being selected by field planner or no alternatives exist), or to optimize truck/excavator type (when truck and excavator types not determined and multiple alternatives available), by clicking either “Optimize Truck Number” button or “Optimize Truck/Excavator Type” button on the UI screen.

4.2 Optimize Haul Job Truck Numbers Function

If users choose to optimize truck numbers, the below

UI window will pop up.

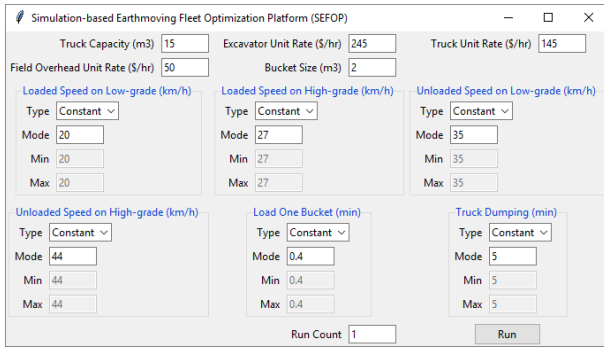


Figure 5. SEFOP User Interface (truck number optimization)

Users need to input “Truck Capacity (m3)”, “Bucket Size (m3)”, “Excavator Unit Rate (\$/hr)”, “Truck Unit Rate (\$/hr)”, “Field Overhead Unit Rate (\$/hr)”, “Loaded Speed on Low-grade (km/h)”, “Loaded Speed on High-grade (km/h)”, “Unloaded Speed on Low-grade (km/h)”, “Unloaded Speed on High-grade (km/h)”, “Load One Bucket (min)”, and “Truck Dumping (min)”.

For truck speed and time inputs, users are allowed to input either deterministic value or distributive values by selecting “Constant” or “Distributed” from dropdown menu “Type”. For distributive inputs, users are requested to input three values as “Mode”, “Min”, and “Max”. The distribution used in SEFOP is triangular distribution.

The last input requested is “Run Count”, to specify how many simulation runs the users expect for the program to iterate. Theoretically, the more run counts, the more accurate the final averaged results are. Once all the requested fields have been inputted, users can click “Run” to obtain the optimized truck numbers for each haul job. A sample output from SEFOP is shown in Figure 6 with optimal truck numbers marked with red box.

| Optimization Results | | |
|--|-----------|-----------|
| Simulation Result of Haul Job1: | | |
| Truck Num | Time (hr) | Cost (\$) |
| 1 | 358.03 | 139631.75 |
| 2 | 179.07 | 95801.59 |
| 3 | 119.49 | 81254.94 |
| 4 | 89.67 | 73975.71 |
| 5 | 85.50 | 82938.66 |
| 6 | 85.50 | 95336.70 |
| 7 | 85.50 | 107734.75 |
| Optimized truck number: 4, Haul job total cost: \$73975.71 | | |
| Total cost: 73975.71428571381 | | |

Figure 6. Optimal Truck Numbers Output

4.3 Optimize Truck/Excavator Type Function

SEFOP is also able to optimize truck/excavator

types together with optimal truck numbers for each haul job by considering the entire project. In SEFOP, if users choose to optimize truck/excavator type, the below UI window will pop up.

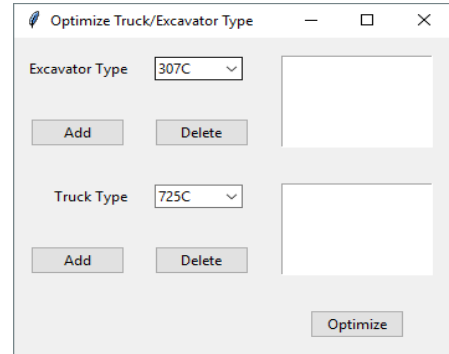


Figure 7. Optimal Truck Numbers Output

The program allows users to input multiple excavator and truck alternatives. Users are also allowed to select excavator type by a dropdown menu including all the common excavator types. Note the SEFOP application only include truck and excavator types from Caterpillar with truck and excavator performance parameters built in the program; the truck and excavator performance parameters can be easily accessed by Caterpillar Handbook [14]. Once excavator type is selected, user need to click “Add” to add the selected excavator type to the excavator pool. Users can delete excavator in the pool by selecting an excavator type in the pool then clicking “Delete”. The truck type input functionalities are the same as excavator. Once alternative trucks and excavators are selected and added to the pools, users click “Optimize” to result in optimal excavator/truck type, together with truck numbers of each haul job and project total cost. A sample output from SEFOP is shown in Figure 8 with optimal truck and excavator types marked with red box.

| Optimization Results | | |
|--|-----------|-----------|
| Excavator: 3200, Truck: 730C | | |
| Simulation Result of Haul Job1: | | |
| Truck Num | Time (hr) | Cost (\$) |
| 1 | 436.88 | 117957.94 |
| 2 | 219.39 | 76786.82 |
| 3 | 172.30 | 74089.69 |
| 4 | 172.32 | 87881.98 |
| 5 | 172.28 | 101645.97 |
| Optimized truck number: 3, Haul job total cost: \$74089.69 | | |
| Simulation Result of Haul Job2: | | |
| Truck Num | Time (hr) | Cost (\$) |
| 1 | 170.12 | 45932.17 |
| 2 | 85.41 | 29893.20 |
| 3 | 71.85 | 30893.82 |
| 4 | 71.87 | 36651.77 |
| 5 | 71.87 | 42405.91 |
| Optimized truck number: 2, Haul job total cost: \$29893.20 | | |

| | | |
|---|-----------|-----------|
| Excavator: 320D, Truck: 735C | | |
| Simulation Result of Haul Job1: | | |
| Truck Num | Time (hr) | Cost (\$) |
| 1 | 410.24 | 112815.40 |
| 2 | 206.84 | 74462.37 |
| 3 | 170.72 | 75969.85 |
| 4 | 170.68 | 90462.31 |
| 5 | 170.67 | 104963.57 |
| Optimized truck number: 2, Haul job total cost: \$74462.37 | | |
| Simulation Result of Haul Job2: | | |
| Truck Num | Time (hr) | Cost (\$) |
| 1 | 159.81 | 43947.53 |
| 2 | 80.76 | 29073.03 |
| 3 | 71.19 | 31679.54 |
| 4 | 71.24 | 37755.90 |
| 5 | 71.20 | 43786.88 |
| Optimized truck number: 2, Haul job total cost: \$29073.03 | | |
| Excavator: 336D, Truck: 730C | | |
| Simulation Result of Haul Job1: | | |
| Truck Num | Time (hr) | Cost (\$) |
| 1 | 549.04 | 178437.33 |
| 2 | 284.75 | 115322.04 |
| 3 | 284.28 | 137878.19 |
| 4 | 284.25 | 160602.84 |
| 5 | 284.20 | 183311.52 |
| Optimized truck number: 2, Haul job total cost: \$115322.04 | | |
| Simulation Result of Haul Job2: | | |
| Truck Num | Time (hr) | Cost (\$) |
| 1 | 216.75 | 70444.68 |
| 2 | 118.49 | 47989.58 |
| 3 | 118.51 | 57476.48 |
| 4 | 118.50 | 66950.79 |
| Optimized truck number: 2, Haul job total cost: \$47989.58 | | |
| Excavator: 336D, Truck: 735C | | |
| Simulation Result of Haul Job1: | | |
| Truck Num | Time (hr) | Cost (\$) |
| 1 | 520.75 | 171847.31 |
| 2 | 281.27 | 116727.51 |
| 3 | 281.08 | 140539.29 |
| 4 | 281.16 | 164476.36 |
| 5 | 281.16 | 188377.50 |
| Optimized truck number: 2, Haul job total cost: \$116727.51 | | |
| Simulation Result of Haul Job2: | | |
| Truck Num | Time (hr) | Cost (\$) |
| 1 | 205.87 | 67937.83 |
| 2 | 117.20 | 48636.76 |
| 3 | 117.17 | 58587.36 |
| 4 | 117.21 | 68565.14 |
| Optimized truck number: 2, Haul job total cost: \$48636.76 | | |
| Simulation Result: | | |
| Best excavator: 320D | | |
| Best truck: 735C | | |
| Total cost: \$103535.40 | | |

Figure 8. Optimal excavator/truck type output

5 Case Study

A rough grading project was utilized for evaluating the proposed method. The rough grading project was the preliminary work package of a camp site construction in Fort McMurray, AB. The field was around 120 hectares, divided into 48 cells each being 150 m by 150 m, as shown in Figure 9.

| | | | | | | | | | | | |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Cell 1 | Cell 2 | Cell 3 | Cell 4 | Cell 5 | Cell 6 | Cell 7 | Cell 8 | Cell 9 | Cell 10 | Cell 11 | Cell 12 |
| -15000 | -3700 | +3700 | +9000 | +9000 | +8000 | -1000 | -11200 | -2300 | -22000 | -6900 | +11200 |
| Cell 13 | Cell 14 | Cell 15 | Cell 16 | Cell 17 | Cell 18 | Cell 19 | Cell 20 | Cell 21 | Cell 22 | Cell 23 | Cell 24 |
| -62600 | +22500 | +23800 | +26000 | +23000 | +22200 | +8100 | -24800 | -9900 | -2200 | +14300 | +7900 |
| Cell 25 | Cell 26 | Cell 27 | Cell 28 | Cell 29 | Cell 30 | Cell 31 | Cell 32 | Cell 33 | Cell 34 | Cell 35 | Cell 36 |
| -3700 | +22500 | +28100 | +23000 | +24300 | +14200 | -12400 | -34400 | -72500 | -28500 | -2500 | 0 |
| Cell 37 | Cell 38 | Cell 39 | Cell 40 | Cell 41 | Cell 42 | Cell 43 | Cell 44 | Cell 45 | Cell 46 | Cell 47 | Cell 48 |
| 0 | 1800 | +2300 | +1200 | +9000 | -5900 | -9900 | -2700 | +2300 | -100 | 0 | 0 |

Figure 9. Cut and fill cells with earth volumes

A total of 43 earthmoving haul jobs together with temporary haul road designs were obtained by employing the analytical method proposed by Li and Lu (2016) on the current case study project, as shown in Table 1. One fleet will be used to perform the earthworks job with one excavator being the lead resource that governs the production capacity. CAT 320D and CAT 336D excavators are available to this project. CAT 735C and 730C articulated trucks are considered for hauling the earth.

To apply SEFOP tool to optimize equipment selection, the 43 haul jobs in Table 1 were inputted into SEFOP, as shown in Figure 10. Alternative trucks and excavators were inputted as shown in Figure 11.

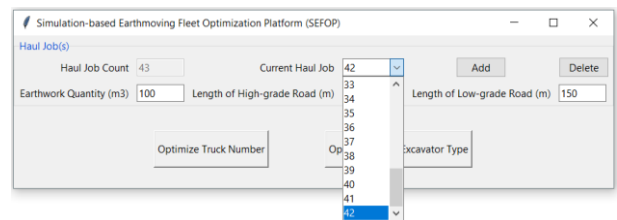


Figure 10. Haul job inputs in SEFOP (start from 0)

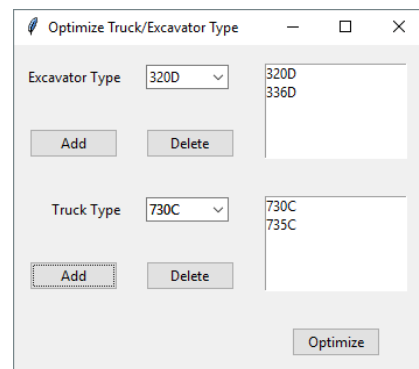


Figure 11. Equipment performance inputs in SEFOP

The simulation run count is set as 1000. By clicking “Run”, the cost, duration, and optimal resource for each haul job of each excavator/truck combination were outputted. In this paper, only the results of the optimal excavator/truck combination were shown, in Table 1.

Table 1. Optimal excavator/truck combination and cost, duration, and resource for each haul job

| Job No | Volume (Bm3) | Haul Distance (m) | | No. of Trucks | Duration (hour) | Cost (\$) |
|-----------------------|--------------|---------------------|--------------------|---------------|-----------------|-----------|
| | | d _{gravel} | d _{rough} | | | |
| 1 | 20000 | 1000 | 0 | 3 | 83.07 | 47764.1 |
| 2 | 15400 | 150 | 212 | 3 | 60.55 | 34814.3 |
| 3 | 19700 | 150 | 150 | 3 | 77.48 | 44550.7 |
| 4 | 7500 | 150 | 0 | 3 | 29.54 | 16984.6 |
| 5 | 15000 | 0 | 212 | 3 | 58.96 | 33901.0 |
| 6 | 3700 | 0 | 150 | 3 | 14.61 | 8398.7 |
| 7 | 1000 | 0 | 150 | 3 | 4.02 | 2311.4 |
| 8 | 4200 | 450 | 424 | 3 | 18.28 | 10513.7 |
| 9 | 7000 | 0 | 300 | 4 | 27.58 | 15856.0 |
| 10 | 2300 | 450 | 574 | 4 | 10.66 | 6126.6 |
| 11 | 7900 | 0 | 362 | 3 | 31.23 | 17954.6 |
| 12 | 4300 | 0 | 300 | 3 | 17.01 | 9781.2 |
| 13 | 9800 | 0 | 212 | 3 | 38.56 | 22173.8 |
| 14 | 6900 | 0 | 150 | 2 | 27.16 | 15614.4 |
| 15 | 2200 | 0 | 150 | 3 | 8.72 | 5011.7 |
| 16 | 2500 | 962 | 150 | 4 | 10.99 | 6319.2 |
| 17 | 15100 | 1112 | 0 | 3 | 55.36 | 31830.4 |
| 18 | 8900 | 662 | 212 | 3 | 33.50 | 19264.7 |
| 19 | 2300 | 0 | 212 | 3 | 9.12 | 5245.9 |
| 20 | 2200 | 0 | 212 | 4 | 8.81 | 6034.1 |
| 21 | 100 | 0 | 150 | 2 | 0.59 | 274.4 |
| 22 | 3500 | 812 | 212 | 4 | 15.22 | 8751.6 |
| 23 | 9000 | 662 | 212 | 4 | 29.39 | 16899.4 |
| 24 | 6800 | 812 | 0 | 3 | 27.32 | 15707.9 |
| 25 | 100 | 512 | 212 | 3 | 0.52 | 301.1 |
| 26 | 3100 | 450 | 212 | 4 | 12.54 | 7212.1 |
| 27 | 23000 | 662 | 0 | 3 | 51.23 | 29459.0 |
| 28 | 4800 | 600 | 0 | 3 | 18.95 | 10895.4 |
| 29 | 22200 | 512 | 0 | 3 | 48.01 | 27603.4 |
| 30 | 8700 | 812 | 212 | 3 | 37.71 | 21685.0 |
| 31 | 1200 | 450 | 424 | 3 | 5.31 | 3051.7 |
| 32 | 16700 | 600 | 0 | 3 | 39.37 | 22635.4 |
| 33 | 8100 | 150 | 0 | 2 | 31.93 | 18361.2 |
| 34 | 12400 | 300 | 0 | 3 | 48.77 | 28043.0 |
| 35 | 20200 | 600 | 0 | 3 | 79.41 | 45663.4 |
| 36 | 14200 | 300 | 0 | 3 | 55.87 | 32126.7 |
| 37 | 2700 | 512 | 424 | 3 | 11.93 | 6862.2 |
| 38 | 2800 | 300 | 212 | 3 | 11.13 | 6398.8 |
| 39 | 7100 | 150 | 212 | 3 | 28.03 | 16117.1 |
| 40 | 5900 | 0 | 150 | 3 | 23.25 | 13369.5 |
| 41 | 1400 | 0 | 150 | 3 | 5.59 | 3214.9 |
| 42 | 900 | 0 | 362 | 3 | 3.66 | 2103.2 |
| 43 | 2800 | 0 | 150 | 2 | 11.08 | 6368.2 |
| Excavator Type | | | | | | 336D |
| Truck Type | | | | | | 730C |

As shown in Table 1, resource allocation, duration, and cost for each given haul job was optimized in terms of minimal operational cost as per methodology in Figure 1. By summing up costs for 43 haul jobs, total earthmoving cost can be obtained. Then, by comparing total earthmoving cost among four fleet combos (320D and 730C, 320D and 735C, 336D and 730C, 336D and 735C), 336D and 730C were selected as optimal solution.

6 Conclusion

A well-designed equipment selection and allocation plan is crucial to the success of earthmoving operations of rough grading projects. In order to help decision makers to select and allocate critical resources, this paper proposed a Simulation-based Earthmoving Fleet Optimization Platform (SEFOP) to automate the fleet selection and allocation process in earthmoving operations in an efficient and user-friendly manner. In specific, this tool provided planner a platform to do “what-if” analysis, providing insight for contractors to select optimal fleet for earthmoving operations. The proposed methodology and SEFOP tool were applied and tested dependent on a real world rough grading projects. It was shown that SEFOP could not only automatically optimize equipment selection and allocate trucks to each haul job consisting of the entire earthmoving job, this intuitive tool could potential improve the business efficiency in resource planning with maximization of profit. Future research will focus on integrating more practical features, such as the nature of soil, the amount of work, the type of earthworks, hydrogeological and other conditions in the simulation process to result in more accurate truck and excavator selection strategy.

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