

## **Developing an Analytical Solution that Mimics Simulation Modeling for Construction Planning: Earthwork Case**

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### **ABSTRACT**

Deriving a reliable earthwork job cost estimate entails analysis of the interaction of numerous variables defined in a highly complex and dynamic system. Using simulation to plan earthwork haul jobs delivers high accuracy in cost estimating. However, given practical limitations of time and expertise, simulation remains prohibitively expensive and rarely applied in the construction field. The development of a pragmatic tool for field applications that would mimic simulation-derived results while consuming less time was thus warranted. In this research, a spreadsheet based analytical tool was developed using data from industry benchmark databases (such as CAT Handbook and RSMeans). Based on a case study, the proposed methodology outperformed commonly used estimating methods and compared closely to the results obtained from simulation in controlled experiments.

### **KEYWORDS**

Earthwork; Hauling; Simulation; SDESA; Planning; Detailed Estimating; Excavator Governing Scenario; Fleet Optimization; Analytical Model.

### **INTRODUCTION**

Heavy construction earthmoving jobs may seem straightforward, but in reality, they entail accounting for sufficient details in connection with numerous factors, such as: job conditions, resource use, and haul road. Evaluation of numerous options in connection with site logistics, selecting equipment, balancing fleet and many other factors substantially complicates the planning and design of any earthmoving operation in earthwork construction. In practice, the project management team is under constant pressure to improve efficiency and productivity. Optimization of resources through balanced resource allocation throughout the course of the project, best equipment selection as per nature of the job, and completion of the earthwork operation with minimum possible cost and time is conducive to attaining the most efficient production rate [1].

Site grading represents preliminary construction work in a large project and accounts for a significant portion of total construction cost. There are numerous challenges faced by earthwork planners during estimating and planning an earthmoving job; making it a time-consuming, tedious and challenging task. Currently, two reliable sources of information are mostly referred to, i.e., RSMeans Online and Caterpillar Performance Handbook, for construction productivity and cost benchmark data in the heavy construction industry [2].

Caterpillar Performance Handbook (hereinafter CATBook) is an annually updated specification logbook containing performance data of various heavy equipment manufactured by Caterpillar

(CAT) Inc. Information for equipment activity time provided in the CATBook is available in the form of lower and upper bounds and most likely values. On the contrary, RSMMeans Online provides averaged equipment performance data, and crew cost data for a particular region in a particular year. Each of these two sources has its own pros and cons in regards to planning and estimating applications. While CAT based estimates are driven by equipment manufacturer data and are ready for feeding operations simulation (e.g. this research used a Monte-Carlo simulation-based tool such as Simplified Discrete Event Simulation Approach or SDESA), they appear far more reliable than RSMMeans Online (RSM) estimates. However, the CATBook and SDESA simulation based method demands long calculation time to prepare inputs and simulation models, and require a large number of iteration cycles to be completed in simulation analysis (which becomes further tedious if the earth haul volume is also large). In contrast, the RSM based method only requires interpolation of cycle times over variable distances without considering different types of trucks or being affected by varying haul road conditions. Also, the number of variables required is limited when using the RSM method. Further, pre-processing of data is not as complex. Thus, unlike simulation based analyses, the results obtained through the RSM method do not require long calculation hours. However, the accuracy of these results may be compromised to a great degree. From a previous comparative study, the RSM method could give rise to about over 30% higher cost estimates than a simulation method based on CAT-SDESA [2].

## LITERATURE REVIEW

On any earthmoving haul job, a grading plan tends to optimize how the total amount of earthwork is executed from cut to fill by using what equipment. It also leads to potentially materializing considerable time, cost and resource savings, and productivity improvement. It was found out that the presence of an approximate optimal earthwork operation plan could result in cost savings from 48% to 74% [3]. During operations in earthmoving projects, fleet composition and earthwork hauling plan are two important drivers of productivity. Although plenty of research has already been done on fleet optimization, it highly depends on formulation of the earthwork hauling plan [4]. Therefore, an optimized earthwork hauling plan is critical to further reduce the amount of hauling efforts and facilitate fleet optimization.

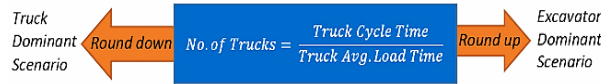
Discrete-event simulation study in [5] revealed that the most important factors affecting crew production rate by descending importance: number of trucks, haul/return time, number of passes per load, and the loading rate. This order also varied per the variation in haul distances.

Once the final grading design has been defined and the total volumes of embankment and excavation have been fixed, the unit cost of earthmoving becomes the wild card in affecting the total direct cost of construction. The commonly used Shortest Route Cut and Fill Problem (SRCFP) model in road construction is aimed to grade a project site with minimum total distance travelled by earthmoving vehicles [3]. As this method considers variation of return distance due to change in excavation sites, the proposed model is much more realistic, and simultaneously, more complicated. Hence, there are three most important factors that describe an earthwork hauling plan: the earth volume to be hauled, the distances through which the material is to be hauled, and the condition of the haul road [6].

Various specification logbooks from equipment manufacturers and classical textbooks suggest the rule of thumb that for best results of output and economy, such a hauling unit (truck) should be selected as is fillable in ‘four to six passes’ of the excavator [7]. However, no justification has been provided for this number of passes. It can be debated that manufacturers generally do not consider two very important factors here: the haul distance, and the effect of different materials on the

loading capacities of the hauler and the excavator bucket. Other factors that are considerably important are related to indirect costs. While indirect costs become high during the course of a project, it is maintained that higher productivity, efficiency and safety performances can be achieved so that the minimum cost per unit earth moved can be realized, whereas, emphasis is shifted towards minimizing the direct costs in regular circumstances in efforts to achieve the same objective [8].

Genetic algorithms were also applied in [9] so as to select the optimal loader-hauler fleet by minimizing total costs. However, the model used in [9] required fixed loader and truck types as inputs. This limited its applicability in the industry. Note that research in [10] extended this work to allow output as a heterogeneous fleet. The model performed well, but only for the test-bed instance; which could become too complex for field application.



**Figure 1.** Effect of selection of different no. of trucks on the excavator production.

While proposing excavator-truck fleet combinations, two production scenarios arise. As the number of trucks is the ratio of truck cycle time to truck loading time, it is generally a decimal number. It can be therefore rounded up and down, where it gives rise to the two production scenarios. Rounding up truck number leads to the excavator dominant scenario, whereas rounding down generates the truck dominant scenario. The dominant resource in field operations has the lower combined total productivity and hence controls the overall production rate on site. Generally, on earthwork sites, excavator is made the leading resource. To ensure this, the excavator dominant scenario should be preferred. A better visual explanation of the two scenarios is presented in Figure 1.

**PROBLEM STATEMENT**

The project is a campground grading site located in Northern Alberta. Relevant features of the jobsite can be found in Table 1.

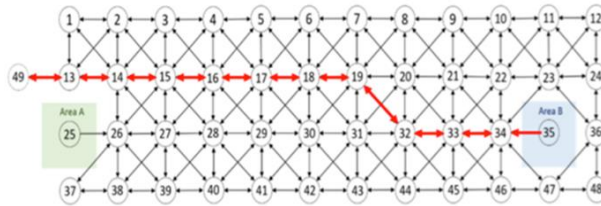
For estimating purposes, the swell factor has been considered and the grading design is roughly balanced in terms of total cut and fill volumes. The proposed grid model for the site shows all the cut volumes denoted with “-” while fill volumes in “+”, as in Figure 2.

The earthmoving jobs defined in this case feature varying depths of excavation (as deep as 3m and as shallow as 1.5m) and different haul route surface conditions; as such, three-point excavator bucket cycle times and trucks speed factors are evaluated for better accuracy. Figure 3 and Figure 4 show two alternative haul road design paths for the project.

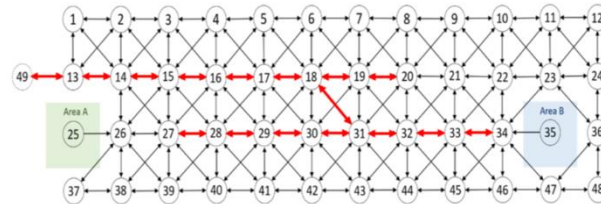
**Table 1.** Project Jobsite Information

Cell 1 -15000	Cell 2 -3700	Cell 3 +3700	Cell 4 +9000	Cell 5 +9000	Cell 6 +8000	Cell 7 -1000	Cell 8 -11200	Cell 9 -2300	Cell 10 -22000	Cell 11 -6900	Cell 12 +11200
Cell 13 -62600	Cell 14 +22500	Cell 15 +33800	Cell 16 +36000	Cell 17 +23000	Cell 18 +22200	Cell 19 +8100	Cell 20 -24800	Cell 21 -9900	Cell 22 -2200	Cell 23 +14300	Cell 24 +7900
Cell 25 -3700	Cell 26 +22500	Cell 27 +28100	Cell 28 +23000	Cell 29 +24300	Cell 30 +14200	Cell 31 -12400	Cell 32 -34400	Cell 33 -72500	Cell 34 -28500	Cell 35 -2500	Cell 36 0
Cell 37 0	Cell 38 -1400	Cell 39 +2300	Cell 40 +1200	Cell 41 +9000	Cell 42 -5900	Cell 43 -9900	Cell 44 -2700	Cell 45 +2300	Cell 46 -100	Cell 47 0	Cell 48 0

**Figure 2.** Designated onsite cut and fill volumes



**Figure 3.** Haul Road Design Path – 1



**Figure 4.** Haul Road Design Path - 2

To perform earthmoving operation between the cut and fill areas, three likely options of articulated trucks, i.e.: CAT 730C, CAT 735C and CAT 740C were considered to be rented; in order to work along with the excavator CAT 336D (owned by contractor). Equipment performance data were taken from the CATBook, 47 Edition, released in January 2017. The combined efficiency factor of 0.75 is applicable to operate all equipment, which accounts for operations efficiency, availability and operator competency.

## METHODOLOGY

The three analytical methods proposed to solve this problem along with their steps are described as follows:

### “CAT-SDESA Simulation” Method

Following steps are involved in this simulation-based method:

- Get truck and excavator performance information to use as inputs from [11].
- Validate haul volume and find out if any volume needs to be shifted outside the grid.
- Calculate cycle distances, no. of excavator buckets required to load the given volume, no. of trucks to haul the said volume, min, avg. and max haul and return times, and the cycle times using the given data. Finally, find out the proposed no. of minimum trucks ‘n’.
- Model the whole situation on SDESA and feed inputs. Perform simulation to get total job completion time (minutes). A minimum of 100 simulation runs should be performed to ensure sampling accuracy. Perform simulation for each of the three truck options on each haul job so as to find out duration for ‘n’ and ‘n+1’ trucks.
- Output of the simulation process is the time taken to complete the given job. Use the time thus obtained to calculate the cost of ‘n’ and ‘n+1’ trucks used on each haul job. Find out which no. of ‘n’ and ‘n+1’ trucks has a combined loading time smaller than the cycle time. Discard that no. trucks and choose the other one for the excavator governing scenario.
- Note that SDESA represents the simplified discrete event simulation approach (SDESA)

originally formalized in [12] in order to streamline the discrete event simulation modelling and make it resemble the experience of critical path scheduling while keeping the essential functionalities and advanced features of simulation. Interested readers can refer to [13] for more details on modelling techniques, computer platform, and practical applications of SDESA.

- A screenshot of this earthwork haul job modelled on SDESA is available in the Appendix.

### “RSM-CAT Interpolation” Method

Following steps are involved in this commonly practiced method:

- Find out the correct line items containing equipment performance data on the RSMMeans Online website. Identify line items with parameters that closely match the corresponding CAT equipment being considered. Interpolate and find required parameters for both excavator and truck.
- Find out cycle time for the RSM truck through interpolation and average cycle time using RSM data. Use the following function in MS Excel to get interpolated RSM Truck Average Cycle Time:  

$$\text{FORECAST}(\text{Truck Cycle Dist.}, \text{OFFSET}(\text{RSM Truck Cycle Time Range}, \text{MATCH}(\text{Truck Cycle Dist.}, \text{RSM Truck Cycle Dist. Range}, 1) - 1, 0, 2), \text{OFFSET}(\text{RSM Truck Cycle Dist. Range}, \text{MATCH}(\text{Truck Cycle Dist.}, \text{RSM Truck Cycle Dist. Range}, 1) - 1, 0, 2))$$
- Find out daily and hourly output production volumes for different sized trucks, each for different cycle times. Find no. of trucks and job cost using this data. Try different numbers of trucks and select the one resulting in the excavator governing scenario as the most cost-effective fleet combination.

### “RSM-CAT Equation” Method

Following steps are involved in this proposed analytical method that is intended to approximate the results as obtained from “CAT-SDESA” simulation while not requiring computer simulation modeling at all:

- This method uses loading and hauling units’ performance data from CATBook. From RSM, it takes truck waiting time and truck cycle distance to find out truck cycle time and then interpolates it over the cycle distance using the combination function of FORECAST, MATCH and OFFSET in MS Excel, similar to “RSM-CAT Interpolation”.
- We search for the maximum cycle distance from given data, and get interpolated RSM truck cycle time for that distance; using regular distance increments (100 m in this case).
- Calculate  $T_2 = T' + T_1$ , where,  $T' = \text{Load Time} + \text{Dump Time}$ ,  $T_1 = \text{CAT Truck Haul} + \text{Return Time}$ .
- Calculate  $T_4 = T_3 - \text{Given Load/Wait/Unload Time}$ ,  $T_3 = \text{RSM Truck Interpolated Cycle Time}$  using combination function of FORECAST, MATCH and OFFSET in MS Excel.
- A hybrid, new and improved truck Load-Unload-Wait time ( $T_6 = T_5 + T'$ ) is calculated using CAT and RSM truck performance inputs. Here,  $T_5 = 0.5 * (T_1 + T_4)$ .
- A new truck Wait/Unload/Load Time ( $T_8 = T_7 + T'$ ) is finally calculated, where  $T_7 = T_3 - T_6$ .

- Lastly,  $T9 = T1 + T8$  is found, which helps in finding the no. of trucks (N), where  $N = T9/\text{Truck Avg. Load Time}$ .
- All relevant parameters are inserted in the RSM cost equation, rephrased here as Equation 1:

$$TC = H * [EC + N * TrC + OHC] \tag{2}$$

Where, TC = Total Cost (\$)

H = Time taken to complete the job (hr) i.e.:

$$H = \frac{\text{Haul Vol.}}{\left( \left( \frac{\text{Truck Capacity} * 60}{\text{Truck Avg. Load Time}} \right) \right)}$$

EC = Excavator Rental Cost (\$/hr) + Excavator Operator Cost (\$/hr)

N = No. of Trucks i.e.:

$$N = \frac{\frac{\text{Dist} * 60}{\text{Truck Speed} * 1000} + \text{LWU Time}}{\text{Truck Avg. Load Time}}$$

TrC = Truck Rental Cost (\$/hr) + Truck Operator Cost (\$/hr), and

OHC = Overhead Cost (\$/hr)

It is notable that the excavator-dominant scenario selection was enabled before arriving at the final cost. This was made possible through using functions in MS Excel. Sum of all job costs amounts to the cost of the project.

Results obtained from this method are then compared with the results obtained from “CAT-SDESA Simulation” method and “RSM-CAT Interpolation” method estimates, and graphically plotted and analyzed.

## COMPARISON OF METHODS

All the three methods were tested on the two layout designs of haul paths in the case study respectively; each with its varying road conditions and truck speeds (except in RSM method; where truck speed and road conditions were assumed constant), and each of the three truck options was evaluated independently subject to the same excavator. This was done to find out the most and the least cost effective out of the three methods being tested.

A few randomly picked jobs out of the 43 in total, as shown in Table 2, were elaborated to clarify the comparison. The three jobs i.e., 19, 36 and 42, from Haul Road Design Path-1 are selected. Job 19 has a haul volume of 2,300 bm<sup>3</sup>, Job 36 has 14,200 bm<sup>3</sup> and Job 42 had 900 bm<sup>3</sup>. Jobs 19 and 42 are completely Rough Road based, and the cycle distances are 424 m and 724 m, respectively. However, Job 36 is a ‘Gravel’ Road based activity, with a cycle distance of 600 m. A tabular comparison of the results obtained from the three methods, as elaborated earlier, is presented in Table 2.

If we observe Table 2, we can see that when CAT 730C is used for Job 19 and it is analysed by all the three available methods/tools, “CAT-SDESA Simulation” results are identified as the most cost effective method in this excavator-dominant scenario. However, “RSM-CAT Equation” method ranks second, whereas, “RSM-CAT Interpolation” (RSM-CAT Graph) turns out to be the most expensive method. A similar pattern is seen in the case of 735C, but in case of 740C, “RSM-CAT Equation” method is the winner, and “RSM-CAT Interpolation” is still the most expensive method.

Job	Haul Design-1								
	CAT 730 C			CAT 735 C			CAT 740 C		
	SDESA-CAT	RSM-CAT Eq.	RSM-CAT Graph	SDESA-CAT	RSM-CAT Eq.	RSM-CAT Graph	SDESA-CAT	RSM-CAT Eq.	RSM-CAT Graph
19	\$12,495.00	\$13,328.00	\$ 16,660.00	\$12,292.00	\$13,170.00	\$ 17,560.00	\$12,922.00	\$11,076.00	\$ 14,820.00
36	\$72,471.00	\$79,968.00	\$ 99,960.00	\$74,630.00	\$74,630.00	\$105,360.00	\$76,609.00	\$65,533.00	\$ 88,920.00
42	\$4,998.00	\$5,831.00	\$ 6,664.00	\$5,268.00	\$6,146.00	\$ 7,024.00	\$5,538.00	\$5,538.00	\$ 5,928.00

**Figure 4.** Comparison of randomly picked jobs on Design Path-1

**Table 2.** D-1 Project Cost and % Difference Comparison using various estimation tools and CAT Trucks

Job No.	Haul Design-1, CAT Trucks					
	730 C	% diff. from SDESA-CAT	735 C	% diff. from SDESA-CAT	740 C	% diff. from SDESA-CAT
SDESA-CAT	\$1,724.31	0.00%	\$1,763.02	0.00%	\$1,825.69	0.00%
RSM-CAT Eq.	\$1,951.55	13.18%	\$1,862.24	5.63%	\$1,627.25	-10.87%
RSM-CAT Graph	\$2,376.55	37.83%	\$2,504.93	42.08%	\$2,202.34	20.63%

**Table 3.** D-2 Project Cost and % Difference Comparison using various estimation tools and CAT Trucks

Job No.	Haul Design-2					
	730 C	% diff. from SDESA-CAT	735 C	% diff. from SDESA-CAT	740 C	% diff. from SDESA-CAT
SDESA-CAT	\$1,775.08	0.00%	\$1,699.19	0.00%	\$1,827.08	0.00%
RSM-CAT Eq.	\$1,964.42	10.67%	\$1,871.90	10.16%	\$1,635.56	-10.48%
RSM-CAT Graph	\$2,376.55	33.88%	\$1,777.26	4.59%	\$2,422.11	32.57%

Job 36 exhibits the exact same pattern of results as of Job 19, except only in the case of 735C, where the results of “CAT-SDESA Simulation” and “RSM-CAT Equation” method are the same. “RSM-CAT Interpolation” method is still the most expensive method here.

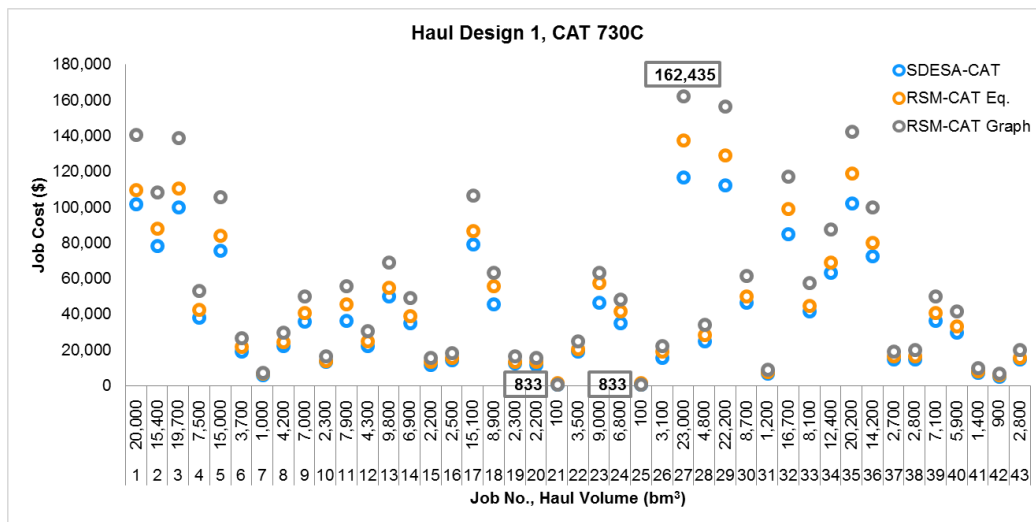
Job 42 also shows a much similar pattern in results as in the previous jobs. Costs are seen continuously rising for each truck as we shift from “CAT-SDESA Simulation” method to “RSM-CAT Interpolation” method. There is another point of convergence in the case of using 740C Truck, where results of “CAT-SDESA Simulation” and “RSM-CAT Interpolation” method become equal.

From the comparison of all 43 haul jobs on both haul paths with all three types of trucks on both varying haul road conditions, it is found that a similar pattern of results is exhibited by the three methods as exhibited by the three randomly picked jobs shown in Table 2. Further, as shown by majority of haul jobs on both haul paths, “CAT-SDESA Simulation” method results in the most cost-effective estimates. Hence, results obtained from this method are taken as a reference benchmark for results obtained from two other methods. Upcoming discussions are based on the same assumption.

### DISCUSSION AND ANALYSIS

Following the experimentation of all the three methods, resulting job cost calculations from all tools and % difference of the remaining two tools from the results of “CAT-SDESA Simulation” method (for both haul design paths) are summarized in Table 4 and Table 3. It can be seen from Table 3, that given Haul Road Design Path-1 project costs obtained using the “CAT-SDESA Simulation” method are lower than those resulting from the other two methods by 5.63% to 42.08%. The exceptional case occurs to Truck Type 740 C in the case of applying the “RSM-CAT Eq.” method, in which the project cost resulting from “CAT-SDESA Simulation” is 10.87% higher. (Note that all cost values are to be multiplied with 1000.) Similar patterns in comparison of resulting project costs can be seen from Table 4 given Haul Design Path-2.

In Figure 5, we can see a scatter plot comparison of all haul jobs of Haul Design Path-1 based on the truck 730C. It can be seen that where the haul volume is large, the difference between cost results is significant. Taking Job 27 for instance, where the haul volume is the largest, i.e., 23,000 bm<sup>3</sup>, where the cost calculated by SDESA-CAT Method is \$116,620, and by “RSM-CAT Interpolation”, it is the most expensive, i.e., \$162,435. However, where there are smaller haul volumes, like in Jobs 21 and 25 (each having haul volume 100 bm<sup>3</sup>), the difference is also much smaller. In fact, unlike jobs with larger haul volumes, where mostly “CAT-SDESA Simulation” Method would result in the most cost-effective and “RSM-CAT Interpolation” method would be the most expensive, for the smallest volume here, the results turn out to be opposite. For Jobs 21 and 25, “RSM-CAT Interpolation” yields the most cost-effective results (\$833).



**Figure 5. D-1, 730C Scatter plot comparison of all jobs**

As mentioned above, interpolated (forecasted) truck cycle times are considered using a constant truck speed for all cycle distances, truck capacities and road conditions. Moreover, wait (idling)



time is considered separately in the new method, in order to simulate a real on-site field problem. It is also noteworthy that Wait Time is not an input when working using SDESA simulation. Such factors are believed to attribute to the observable differences against SDESA simulation produced results.

## CONCLUSION

The fact that the results yielded by the new method/tool, i.e., “RSM-CAT Equation” method vary between 13.18% (positive side) to -10.87% (negative side) in both paths (with all types of CAT Trucks) against those of “CAT-SDESA Simulation” method indicates that the “RSM-CAT Equation” method is reliable, effective and comparable with the counterpart method based on simulation model to a good degree.

Considering the “CAT-SDESA Simulation” method results as a reference, it can be observed that compared to SDESA simulation results, the results yielded by the “RSM-CAT Equation” method diverge only marginally, within a narrow range (-10.87% to 13.18% as extreme cases). This deviation can be attributed to the approximation of a few direct and indirect inputs from the RSMMeans Online in this new method.

No. of inputs required for the newly proposed “RSM-CAT Equation” method are fewer than required by its both other counterparts. Hence, there is a lesser probability of incurring human/manual entry errors.

The proposed “RSM-CAT Equation” method can be applied to different excavator and truck fleet combinations. This paves the way towards a wider acceptance of the tool.

Lesser no. of inputs also reduces the need to pre-process and prepare data for further use at later stages. This ultimately results in time savings, which could mean that this method is readily applicable to field operations.

The significant increase in the accuracy of results provided by the “RSM-CAT Equation” method compared to the “RSM-CAT Interpolation” method can be attributed to the calculation of separate haul and return times by segregating truck speeds based on road types, haul and return actions, and their corresponding cycle distances. As a result, this would eliminate the need to use interpolated values, which plays a pivotal role in improving the quality of results.

From Figure 5, it can be concluded that results obtained from “RSM-CAT Interpolation” method are more applicable in the extreme sides than the newly proposed “RSM-CAT Equation” method and the “CAT-SDESA Simulation” method. This has been confirmed by the results obtained for both haul path designs. In light of these results, we can conclude that the newly proposed method, i.e., “RSM-CAT Equation” method gives better cost estimates than “RSM-CAT Interpolation” method, and that it can be properly used as an alternative to the time-consuming “CAT-SDESA Simulation” method by planners and estimators in the field, without having to worry about obtaining unreliable job costs resulting from direct interpolation on RSM data (i.e. “RSM-CAT Interpolation” method.)

## RECOMMENDATION

It is recommended to use this tool on more and different test cases in order to fully qualify the reliability of the “RSM-CAT Equation” method. Data should be taken from different excavator and truck manufacturers so that formation of both homogeneous (same manufacturer) and heterogeneous (different manufacturers) fleet combinations could be analyzed. Results should be verified by comparing them against the ones resulting from “CAT-SDESA Simulation” method and “RSM-CAT Interpolation” method respectively as the actual data for the specific job being

planned are generally not available. This will further enhance confidence in this newly proposed tool.

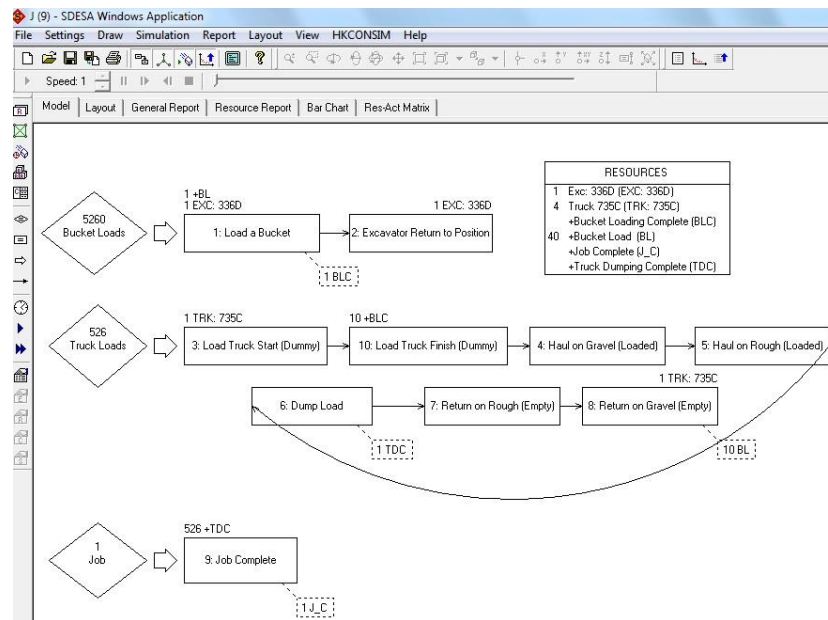
Apart from excavator and truck combinations, this method may also be applied to different types of loading and hauling unit combinations. If results obtained by various loading and hauling unit combinations (both homogeneous and heterogeneous) are consistent using this method, some newer and more accurate rules of thumb can be developed for field application, which may further shorten the estimating time and yet produce meaningful and reliable results in a short turnaround time.

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## APPENDIX

See Figure 6 from the “CAT-SDESA Simulation” method for a randomly selected job.



**Figure 6.** Randomly picked earthmoving job modelled on SDESA

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