Optimal Selection of Construction Machinery for Earthmoving Operations Using DES-ABM Hybrid Approach

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- Earthwork
- Cost
- Construction Machinery
- Simulation
- Agent-Based Modeling
- Discrete Event Method

Abstract
In the construction of infrastructure facilities, earthworks usually represent a large and significant part of the project in terms of quantities and thus costs. Therefore, it is important to make the right selection of machinery to perform these works in order to keep costs as low as possible. The paper presents a simulation model for the selection of a more favorable variant for excavation and transport of soil material. The hybrid approach, a Discrete Event method in combination with Agent Modeling, was used to create the model, and the model was developed in the AnyLogic software package. Based on the data to be entered at the beginning of the simulation, the model calculates the total costs, total duration, as well as unit costs for two combinations of machines that can be used for excavation and transport of soil. Depending on the set criteria, minimum duration or minimum costs, the optimal combination is chosen. The model can also be applied to various analyses by changing the input parameters.

1. Introduction
In terms of volume and costs, earthworks can be ranked among the most extensive and significant works in construction. Excavation and transport of soil requires significant financial investments in the purchase or rental of heavy machinery, and in addition, exploitation and maintenance costs are significant. Therefore, optimal planning and utilization of this machinery is vital for project management. If the right and optimal choice of machinery is made, it can lead to significant savings in time and costs of earthworks.

There are a number of different methods used in machinery selection procedures, such as linear programming, genetic algorithms, neural networks, etc. In recent times, a significant share is occupied by simulation methods and techniques.

The simulation has been used for decades in modeling construction processes, especially in large-scale operations, such as earthworks, where heavy and expensive machinery and equipment are used. Simulation can be used as a planning tool, to analyze the time and cost of execution of works. Current methods used in earthwork simulation are based on Discrete Event Simulation (DES), with recent efforts to introduce system dynamics (SD) into the hybrid DES-SD approach. Another hybrid approach is also used, a combination of discrete event simulation (DES) with the Agent Modeling Method (ABM).

A review of the available literature highlights the works where the simulation and optimization of the process of performing earthworks in construction was processed.

Zankou and Khoury (2015) [1] create two models to represent earthmoving operations, the DES model and the ABM model. The purpose of their research is to visually show the interactions between different resources and entities in earthmoving operations and to compare the DES and ABM approaches with an assessment of the advantages and disadvantages of both methods. Finally, consideration, discussion and the possibility of combining these two approaches in a multi-method are given.

Jabry and Zayed (2017) [2] applied Agent Based Modeling (ABM) and developed a Java-based application called Agent-Based Simulator for Earthmoving Operations (ABSEMO). Based on the case study on the construction of the dam, the verification of the proposed model was performed. A comparison of the results obtained by this approach with the results obtained based on the existing DES model for the same operations were performed. The percentage difference is 0.42%, which confirmed the accuracy of the new model.

In paper [3] a Multi-Agent System (MAS) that combines Location-based Guidance Systems (LGS) technology with advanced safety management methods to support the equipment operators on the construction site are designed. “A two-layer safety mechanism is proposed for the safety management in the MAS that enables proactive and reactive responses for the prevention of equipment-related collisions on the construction site. A case study is developed to validate the proposed method. It is found that the proposed MAS structure is able to effectively address the fleet-level coordination between earthwork equipment and potentially improve the safety of earthwork projects.” [3]

The authors in [4] present a working model of a tunnel excavation machine developed in AnyLogic software using all three methods: DES, ABM and SD. The model was applied in a case study on an 8000 m long tunnel. No delays were considered in the first experiment. In the second experiment, delays are considered but simplifications are taken into account in terms of material landfills and soil
the influence of different parameters. This stochasticity of duration is
2.1. Problem statement
An impact on poor results in achieving the project objectives.

The focus of this study is the rapid decision of selecting optimal
arrangement of equipment to maximize global resource utilization. In

Marquis and Jrade (2017) [7] have developed a system for the optimal
selection of excavating and transport machines for earthworks. By
applying linear programming and constrained-based simulation, a
model was obtained which, based on costs, determines the optimum
fleet necessary to execute the construction of the dam.

Another study conducted by Marzouk and Moselhi (2003) [8]
deals with costs without considering complex factors in the analysis of the work
of machinery for earthworks. An object-oriented simulation model for
earthworks has been developed, consisting of a simulation program,
a database, a cost application, and an optimization module.

Moselhi and Alshibani (2009) [9] present optimization model for
earthmoving operations in heavy civil engineering projects. The
developed model utilizes genetic algorithm, linear programming, and
geographic information systems and it has been implemented in
prototype software, using object-oriented programming.

Mohsenijam et al (2020) [10] have been developed two simulation
models: Decision-Support Model and Estimation Model, in the
Symphony modeling. The Decision-Support Model provides the best
arrangement of equipment to maximize global resource utilization. In
contrast, the Estimation Model captures more of the project details
and provides a comparison of various equipment arrangements based
on their cost.

The subject and goal of this research is the formation of a simulation
model which will serve to decide and select a more favorable
combination of machinery for the needs of excavation and transport
of soil material. The simulation model was developed in an object-
oriented Java environment using the AnyLogic software package.
Based on the input data: unit work costs of individual machines in the
group, capacity and number of machines, as well as the amount of soil
to be excavated, the output data is the duration of excavation and
transport, total costs and unit costs for given variants. The choice of
a more favorable variant is made on the basis of a given criterion.

2. Methodology
2.1. Problem statement
The focus of this study is in rapid decision of selection optimal
combination of machinery for earthmoving operations. By applying
the simulation of discrete events, earthmoving operations are
presented in a simple way in order to enable easy understanding of
the process and display a clear picture of it. A gap is in neglecting the
stochastic nature of earthmoving operations. Selection of machinery
in common practice is based on average operating cycles [10]. This
has an impact on poor results in achieving the project objectives.

The uncertainty of earthmoving operations is reflected in the
duration of operations and the performances of machines that are not
always the same, deterministic size, but are subject to change under
the influence of different parameters. This stochasticity of duration is
considered through the distribution of probabilities that are included in
the corresponding parameters when forming the simulation model.

2.2. Hybrid simulation approach - DES and ABM technique
The cyclical mode of the earthmoving operations provides a good
basis for the application of simulation as a suitable tool for planning
and forecasting. Like other processes in construction, earthmoving
operations are processes with a stochastic nature, so they are suitable
for the application of simulation methods.

“Discrete event simulation (DES) adopts a process-oriented approach,
the dynamics of the system are represented as a sequence of
operations performed given entities” [11]. In classic discrete event tools,
the entities are passive and can only have attributes that affect the
way they are handled [12]. “In an agent based modeling (ABM) the
modeler describes the system from the point of view of individual
objects that may interact with each other and with the environment”
[11]. In AnyLogic multithreaded simulation software, entities and
resources can be modeled as agents with individual behavior and
state changes [12].

2.3. The machinery for earthmoving operations
The paper discusses the process of excavation of soil material with
transport and unloading at the landfill. For the needs of excavation of
soil material, it is possible to apply different machinery, depending on
the category of the soil, the manner and size of excavation, the
machinery that the company owns, etc. For the usual categories of soil
III - IV, that mostly occur in this area, excavators and bulldozers for
excavation are most often used, and for the needs of transport,
dumper trucks or tipper trucks are used. Due to the frequency of
application of these machines, these two possible combinations of
machines are analyzed in this paper. The first combination consists of
an excavator and trucks (Fig. 1), while the second combination
consists of a bulldozer, loader and trucks (Fig. 2).

Figure 1. Schema of earthmoving operations (1st variant)
Figure 2. Schema of earthmoving operations (2nd variant)
the earthmoving operations for the proposed two machine combinations.

The model is developed for work with one main machine, in the first variant, that is an excavator, and in the second one that is bulldozer. One loader is planned too, but a number of trucks are changeable for both of the variant.

2.4. Earthmoving operations costs

Estimation of work costs of construction machinery is most accurately performed on the basis of a historical database. If it does not exist (which is often the case in practice), the recommendation of the manufacturer of machinery adapted to the real construction conditions or some other methodology, sufficiently precise and accepted by the investor [13] is used.

Cost of machinery work can be direct and indirect. Direct costs are related to the operation of the machine and include the consumption of fuel, filters, oil, grease, labor. They are expressed directly per hour of machine operation. The second type of costs, that is not directly related to production, includes fixed asset costs, overhead and other general costs, costs related to insurance, interest, repair, depreciation, etc.

All or some of the listed costs participate in the cost structure and unit price of some machines, depending on the specific situation. The cost of operating hours of the machines considered in this paper is used as input for the simulation experiment. For the example presented in the paper, the current market values of the working hour for the considered machinery expressed in RSD / h (in Republic Serbian dinars per hour) were adopted.

3. Development of the simulation model

3.1. The model description

The simulation model was developed in AnyLogic software, using a hybrid approach, a combination of DES and ABM. The corresponding blocks represent the individual operations in the earthmoving works, and by connecting these blocks, the charts process was obtained (Fig. 3). This is a typical application of the DES method. However, by including the ABM method, the model gained in comprehensiveness by introducing agents. Trucks and bulldozers are the agents in the model.

In each of the blocks, variable values are set using the appropriate parameters. Defining variables enables monitoring of changes in the model during the simulation. Also, bar charts and plot charts are defined, that visually enable the display of the state in the model in each time interval during the simulation. The behavior of the model is defined by entering additional Java code which completes the system and shows it in more detail. The visual representation of earthmoving operations is enabled by 2D animation, shown above process chart on figure 3.

3.2. Input parameters

Both of proposed variant start with source block that generated a given number of agents (trucks) that go to queue block waiting to be loaded in excavation1 block (variant 1) or loading2 block (variant 2). Duration (in minutes) of excavating and loading for variant 1 is calculated as: (agent.capacity1 / (54.98 * excavatorCapacity)) * 60 (fig. 4), according to author's experience. Once loaded, truck go true transport block in that duration is defined by distance and speed. Duration (in minutes) of loading for variant 2 is calculated as: (agent.capacity2 / (47.41 * loaderCapacity)) * 60, according to author's experience.

Parameter transport distance represents distance from excavating area to unloading area. Transport speed is average hauling speed and returning speed is average speed truck is returning, after unloading process. Both of them have stochastic nature and used as triangular function of probability.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck capacity</td>
<td>11</td>
<td>m³</td>
</tr>
<tr>
<td>Excavator bucket capacity</td>
<td>Set on start of simulation</td>
<td></td>
</tr>
<tr>
<td>Bulldozer blade height</td>
<td>Set on start of simulation</td>
<td>m</td>
</tr>
<tr>
<td>Bulldozer blade width</td>
<td>Set on start of simulation</td>
<td>m</td>
</tr>
<tr>
<td>Loader bucket capacity</td>
<td>Set on start of simulation</td>
<td>m³</td>
</tr>
<tr>
<td>Quantity to excavate</td>
<td>Set on start of simulation</td>
<td>m³</td>
</tr>
<tr>
<td>Transport distance</td>
<td>Set on start of simulation</td>
<td>km</td>
</tr>
<tr>
<td>Excavator cost</td>
<td>Set on start of simulation</td>
<td>RSD/h</td>
</tr>
<tr>
<td>Bulldozer cost</td>
<td>Set on start of simulation</td>
<td>RSD/h</td>
</tr>
<tr>
<td>Loader cost</td>
<td>Set on start of simulation</td>
<td>RSD/h</td>
</tr>
<tr>
<td>Truck cost</td>
<td>Set on start of simulation</td>
<td>RSD/m³</td>
</tr>
<tr>
<td>Number of trucks (variant 1)</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Number of trucks (variant 2)</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Transport speed</td>
<td>triangular (15, 25, 30)</td>
<td>km/h</td>
</tr>
<tr>
<td>Returning speed</td>
<td>triangular (30, 35, 40)</td>
<td>km/h</td>
</tr>
</tbody>
</table>
3.3. Output parameters

Setting the appropriate parameters starts the simulation experiment. Figure 5 shows the initial screen of the simulation experiment.

During the simulation, changes in the system can be monitored through a series of variables, 2D animation (Fig. 6) and charts (Fig. 7).

For the analysis and testing of the developed model, examples were made for excavation of 1000 cubic meters of soil that was transported with a different number of trucks to be unloaded at a distance of 5.8 km. The number of trucks has been varied from 1 to 10. Utilization of machinery, total time and total cost are obtained in experiment and shown in table 2 and table 3.

<table>
<thead>
<tr>
<th>Number of trucks</th>
<th>Utilization excavator</th>
<th>Utilization bulldozer</th>
<th>Utilization loader</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.196</td>
<td>0.583</td>
<td>0.178</td>
</tr>
<tr>
<td>2</td>
<td>0.391</td>
<td>0.581</td>
<td>0.354</td>
</tr>
<tr>
<td>3</td>
<td>0.585</td>
<td>0.581</td>
<td>0.527</td>
</tr>
<tr>
<td>4</td>
<td>0.782</td>
<td>0.582</td>
<td>0.686</td>
</tr>
<tr>
<td>5</td>
<td>0.971</td>
<td>0.581</td>
<td>0.687</td>
</tr>
<tr>
<td>6</td>
<td>1.000</td>
<td>0.580</td>
<td>0.687</td>
</tr>
<tr>
<td>7</td>
<td>1.000</td>
<td>0.579</td>
<td>0.686</td>
</tr>
<tr>
<td>8</td>
<td>1.000</td>
<td>0.580</td>
<td>0.688</td>
</tr>
<tr>
<td>9</td>
<td>1.000</td>
<td>0.581</td>
<td>0.679</td>
</tr>
<tr>
<td>10</td>
<td>1.000</td>
<td>0.581</td>
<td>0.679</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of trucks</th>
<th>Total time (hour)</th>
<th>Total cost (RSD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variant 1</td>
<td>Variant 2</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>46.39</td>
<td>142,471</td>
</tr>
<tr>
<td>2</td>
<td>23.19</td>
<td>142,471</td>
</tr>
<tr>
<td>3</td>
<td>15.46</td>
<td>142,471</td>
</tr>
<tr>
<td>4</td>
<td>11.54</td>
<td>142,471</td>
</tr>
<tr>
<td>5</td>
<td>9.28</td>
<td>142,471</td>
</tr>
<tr>
<td>6</td>
<td>9.00</td>
<td>142,471</td>
</tr>
<tr>
<td>7</td>
<td>9.00</td>
<td>142,471</td>
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<tr>
<td>8</td>
<td>9.00</td>
<td>142,471</td>
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<tr>
<td>9</td>
<td>9.00</td>
<td>142,471</td>
</tr>
<tr>
<td>10</td>
<td>9.00</td>
<td>142,471</td>
</tr>
</tbody>
</table>

4. Analysis of the simulation results

By analyzing the model, it can be concluded that the simulation gives realistic and expected results. Based on the graphs showing the price change during the simulation (Fig. 7), it can be seen that for both combinations the total price increases with increasing quantity, i.e., the unit price decreases. So for all quantities from null to considered quantity 1000 cubic meter, variant 1 is lower cost.
5. Conclusion

In this paper DES and ABM simulation technique as hybrid approach have been used to develop the model for optimal choice of earthmoving machinery. The model is clearly and simply to use in solving and decision of which variant is better to use. Based on the amount of soil to be excavated and the unit prices of machine operation and their capacities, it is very simple and easy to get the total costs and the total duration of excavation and transport. If a lower price or shorter duration is chosen as a criterion, it is possible to choose the optimal solution.

The limitation of the model is that it only serves to choose between two proposed variants. Also, the model is developed for one excavator, bulldozer and loader, although, the number of trucks is changeable and that is set on start of simulation. In terms of costs, only unit costs of machine operation were introduced as input data at the start of the simulation. Further research should focus on expanding the cost structure and studying them in more detail by analyzing direct and indirect costs.

The model can be recommended as an appropriate tool for rapid selection and decision about machinery that be used for earthmoving operations.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. 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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