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# Improving Materials logistics plan in Road Construction Projects Using Discrete Event Simulation

## Abstract

**Purpose**: Motivated by the high cost of material movements in road construction projects, past studies have used analytical methods to optimize materials logistics plans. A key shortcoming of these methods is their inability to capture the uncertain, dynamic, and complex characteristics of the road construction material logistics. Failure to incorporate these characteristics can lead to sub-optimal results. This research proposes the use of discrete event simulation (DES) to address the existing shortfall. **Methodology**: Despite the powerful capabilities of DES models in capturing the operational complexities of construction projects, they have not been previously utilized to optimize the material logistics of road construction projects. The proposed DES-based method in this research captures the operational details of material logistics and uses a heuristic approach to overcome the combinatorial problem of numerous choices. The method was applied to a 63.5 km real-world road construction project case to demonstrate its capabilities. **Findings**: Six different material types from 28 material sources were used in the case. Approximately 1.5 percent of the material logistics costs were saved by following the proposed method and choosing appropriate material sources. **Originality**: This research contributes to the body of knowledge by leveraging the capabilities of DES and presenting a novel method for improving the materials logistics plan of road construction projects. The proposed method provides practitioners with the basis for capturing the key operational details that were overlooked in the past. The proposed method can be adopted in road construction projects to reduce the overall material procurement cost.

*Keywords: Material logistics, road construction, discrete event simulation, construction management.*

# INTRODUCTION

Roads are massive structures built from materials such as aggregate, concrete, bitumen, and asphalt. These materials are typically hauled over a distance ranging from several kilometers to tens or even hundreds of kilometers to reach their designated locations. The need to handle the massive amounts of materials is a key contributor to the considerable cost of road construction projects. It is estimated that material handling operations contribute to 50 - 65% of road construction project costs (Akimovs and Riga 2013). Material transportation is an important part of material handling operations. For instance, Akimovs and Riga (2013) demonstrated that on average transportation cost made up around 25% of preparation costs, 39% of land-work costs, 25% of construction costs, and 24% of demolition costs.

Typically, several hauling trucks have to travel between different material sources and the road construction job site. As a road construction project advances, the job site location moves. Consequently, the hauling distance i.e., the distance between the material source and the job site location, dynamically changes over time. Figure 1 illustrates this concept by presenting the distance change from material source 1 and source 2 to the job site from the early stages of a road construction project (Figure 1.a) to the later stages (Figure 1.b). In the early stages of the project (Figure 1.a), Source 1 is closer to the job site and it is likely that procuring materials from Source 1 is more cost-effective than Source 2. However, as the project advances to its later stages (Figure 1.b), Source 2 becomes more cost-effective than Source 1. It should be noted that the material price offered by Source 1 and Source 2 also affects the cost-effectiveness. Not surprisingly, for some materials, including various types of aggregates, the transportation cost quickly outweighs the original material price when the material hauling distance increases. According to 2017 cost index data published by the Management and Planning Organization of Iran (MPOI, 2017), the average price aggregate material is around 5$ per ton while its mean transportation cost is 0.25$ per tonne-kilometer. It means the transportation cost exceeds the material price for the hauling distances beyond 20 kilometers.

[Insert Figure 1 here]

The Council of Supply Chain Management Professionals (CSCMP, 2013, p. 117) defines logistics as "planning, implementing, and controlling procedures for the efficient and effective transportation and storage of goods including services, and related information from the point of origin to the point of consumption". The materials logistics plan outlines decisions regarding the supply of different material types from different material sources in various parts of the project. The availability of multiple material sources for each material type and the variety of influential factors make the materials logistics plan a complex optimization problem in many road construction projects (Jaskowski et al., 2018). Sample influential factors are project progress rate (Burdett and Kozan, 2014), material type (Kim et al. 2012), volume of material (Zayed et al. 2008; Burdett and Kozan, 2014), material price (Zayed et al. 2008; Jaskowski et al., 2018), material source distance (Burdett and Kozan, 2014), equipment type (Kim et al. 2012; Jaskowski et al., 2018), and equipment cost (Zayed et al. 2008). In practice, construction project managers develop the materials logistics plan based on analytical techniques and incorporate factors that reflect their experience. However, these analytical techniques cannot properly capture the uncertain and dynamic nature of influential factors (Burdett and Kozan, 2014). In this research, a novel simulation-based method for reducing material logistics costs in road construction projects was proposed. The proposed method addresses the existing gap of past research to capture uncertain, dynamic, and complex impacts of influential factors using discrete event simulation capabilities.

The structure of the remainder of this manuscript is as follows. First, the state of knowledge in materials logistics planning as a complex problem is reviewed and discussed. Then, the capabilities of discrete event simulation in capturing the complex behavior of the system is reviewed from the literature. Next, the building blocks of the proposed method are discussed. Following that, the applicability of the proposed method to a real-world road construction project is investigated using the data from a 63.5 km road construction project in the south-east of Iran. Finally, insights and conclusions are presented.

# STATE OF KNOWLEDGE IN MATERIALS LOGISTICS PLANNING

Optimizing the cost of material supply is one of the main objectives of many construction projects (Jaskowski et al., 2018). The high cost of moving large quantities of material in road construction projects has inspired many materials logistics optimization efforts. Nassar and Hosny (2012) used the Particle Swarm Optimization (PSO) to minimize the total material hauling distance between cuts and fills. They demonstrated that the PSO calculation speed is reasonably higher than the traditional branch-and-bound technique in large problems with more than 70 locations. Furthermore, they incorporated vehicle performance characteristics, grade resistance, rolling resistance, and fuel consumption in the problem which is difficult to capture in traditional analytical methods. de Lima et al. (2013) proposed a linear programming model that relates the geometric and geotechnical features of a road construction site to the material allocation and aims to identify the plan with the minimum construction cost. They developed a software package based on their proposed method to automate the earthmoving and paving planning process.

Gwak et al. (2016) proposed a genetic algorithm-based method that incorporates stochastic variables for the haul-route optimization based on the equipment travel time and fuel consumption. They improved the computation speed of the earthmoving problem compared to past research. Dell'Amico et al. (2016) developed a decision support system for scheduling the material logistics problem in construction projects based on linear programming. Krantz et al. (2017) introduced a step-by-step guide for incorporating the carbon dioxide emissions in the materials logistics plan development of the construction projects. Güden and Süral (2017) developed a polynomial dynamic programming algorithm to minimize overall earthmoving costs. In this model, for the first time, the supplier and the customer decisions on reproducing and returning materials were incorporated in the model. Choudhari and Tindwani (2017) modeled the procurement and distribution of raw materials in the entire road construction project using a linear programming model.

The review of the literature indicates that the past efforts in optimizing the materials logistics plan for road construction projects are generally based on analytical methods such as mathematical programming and meta-heuristic techniques. The main goal of the existing models is to introduce applicable methods for reducing the travel distance (Son et al., 2005) or balancing cuts and fills in the earthmoving operations (Ji et al., 2010). Nevertheless, the existing analytical approaches are unable to incorporate dynamic and uncertain interactions of road construction operations. Dynamic change in the road construction site location, delays in the material arrival, resource constraints, and deviated productivity rates are examples of the commonly seen operational issues that analytical methods are unable to capture. These dynamic and uncertain interactions augment the complexity of the material logistics problem. Without considerable simplifying assumptions, analytical models become too complex and difficult to use by practitioners for materials logistics planning (Jaskowski, 2014). These simplifications, however, can lead to sub-optimal results and limit the applicability of the models. This research proposes the use of a simulation-based technique to address the existing gap of the analytical models.

# DISCRETE EVENT SIMULATION OF COMPLEX OPERATIONAL PROBLEMS

Interactions among multiple real-world elements increase the complexity to the level that can only be analyzed using simulation-based techniques (Robinson, 2005). Researchers and practitioners have adopted various simulation techniques to investigate diverse complex problems in the construction industry. Among various simulation-based techniques, discrete event simulation (DES) is a well-known tool for modeling complex systems that supply materials and services (Robinson, 2005; Jahangirian et al. 2010; Greasley and Owen, 2018). DES provides a set of modeling elements that can properly be utilized to capture operational details of systems, including workers, materials, and equipment movement and interactions. This capability of DES models has augmented their application to a variety of sectors, including manufacturing (Negahban, and Smith, 2014; Cigolini et al., 2014; Barlas and Heavy, 2016), healthcare (Baril et al. 2016; Zeigler 2016;

DeRienzo et al. 2017), resilience (Cimellaro et al. 2017; Miles, 2018), disaster recovery (Longman and Miles, 2019; Na and Banerjee 2019), and transportation (Carteni and de Luca, 2012; Fanti et al. 2015; Kogler and Rauch, 2018). DES has also been widely used in different aspects of the construction sector, such as earthmoving (Shawki et al. 2015), lifting (Nam et al. 2002), piling (Zayed and Halpin 2004), pipeline construction (Luo and Najafi 2007), steel construction (Alvanchi et al. 2011a), excavation operation (Marzouk et al. 2010), tunneling (Al-Bataineh et al. 2013), construction safety (Baniassadi et al. 2018), and environmental impact assessment of construction project schedule (Alvanchi et al. 2020).

Past studies have utilized DES-based techniques to model various activities related to road construction projects. However, the majority of these research efforts focused on improving combinations of equipment fleet and activity sequences. Smith et al. (1995) used DES to improve truck fleet in the earthmoving operations. Hajjar and AbouRizk (1996) built a special purpose simulation template for facilitating the earthmoving simulation model development process. Clegg et al. (1997) reduced equipment congestion. Martinez (1998) developed a special-purpose simulation-modeling template for facilitating the planning of earthmoving equipment. Farrar et al. (2004) investigated the impacts of adopting lean production concepts in road construction projects. Han et al. (2005) used real-time data from GPS (global positioning system) of the earthmoving equipment to simulate and improve productivity in the earthmoving operations. Martinez (2009) combined linear programming and the DES to improve the productivity of earthmoving operations. Ahn et al. (2009) evaluated emissions from earthmoving equipment in construction operations. Cheng et al. (2010) optimized the number of earthmoving equipment. Ji et al. (2011) improved cuts and fills in the earthmoving operations to minimize on-site material handling. Mostafavi et al. (2012) improved the productivity of night-time paving activities. Labban et al. (2013) proposed a new framework for making the process of building simulation models accessible to the stakeholders without simulation expertise. They built an asphalt paving simulator using the proposed framework. Akhavian and Behzadan (2013) proposed a methodology for updating construction fleet performance in the simulation model based on the most recent data to enhance the accuracy of the model. A review of the past research indicates that DES has not been applied to material source selection and the materials logistics plan optimization in the road construction projects despite its capabilities.

# PROPOSED METHOD

The proposed DES-based method in this research has four main parts, including 1) recognizing project specifications and details, 2) overcoming the challenge of too many alternatives, 3) developing DES models of the identified scenarios, and 4) evaluating different scenarios. In the following, each part is discussed in detail.

### Recognizing Project Specifications and Details

To be able to develop simulation models of road construction projects, a solid understanding of different parts of the projects has to be established. The required equipment and their productivity rate, activity sequences and durations, volumes and types of materials, cuts and fills locations, and cost rates are the main information to be collected. Depending on the nature of the information, a combination of data collection techniques, including the study of project documents, project observation, data sampling, use of historical data, and expert judgment, needs to be adopted. The operational uncertainty involved in different parts of the project is captured in the form of statistical distributions. The goodness of fit tests (Banks et al., 2005, pp. 269-305) is used to identify the statistical distributions that can properly describe the variation of the input data. Since the focus of the simulation model is to improve material logistics, all possible material sources have to be identified. The location of each material source is used to dynamically calculate the driving distance to the project's job site in different periods of the project. A conditional equation needs to be developed to calculate the material hauling distances from various material sources depending on the project's progress and the directions of the access roads. Equation 1 represents this conditional equation for a sample material source, e.g., material source 1 represented in Figure 1, depending on the project progress.

$$Material\ source\ distance(km) = \begin{cases} a(km) + b(km) - progress(km);\ if\ prgress(km) < a(km) \\ a(km) - b(km) + progress(km);\ if\ prgress(km) > a(km) \end{cases} \quad (1)$$

Where:
"a" is the distance of the access road between the material source location and the road route
"b" is the distance between the project's start point and where the access road and the road route intersect
"progress" represents the distance between the project's start point and the job site location

**DES Model Development Steps**

A DES model simulates a project by following the activity sequences and the resulting scheduled events in the future event list (Banks et al., 2005, pp. 61-83). In the model development process, first, the project's execution logic is recognized and the DES model elements are designed. Next, the data items required for the development of the actual DES models of different available project scenarios are collected. The actual models of the different project scenarios are then developed, verified, and validated based on the collected information. Finally, the developed models are run to evaluate the cost performance of different available scenarios and introduce the best available scenarios. Detailed explanations of various stages of the DES model development is provided by Banks et al. (2005). Following, the required modeling elements and the identified logic of the material logistics in a typical road construction project are presented.

Entities are the main elements and driving forces of every DES model. In the proposed method, road segments are designed as the main entities of DES models. The length of each segment can vary from one centimeter to several kilometers based on the construction methods and modeling approach adopted. All segment-entities have to be delivered in the DES model for a road to be completely constructed. During a road construction project, several layers of materials have to be sequentially placed on a road segment. From the DES modeling perspective, a segment-entity evolves as the project advances from an untouched ground to a completed road segment-entity. For example, sub-grade material-entities are merged with untouched segment-entities to form sub-graded segment-entities. Sub-base material-entities are merged with sub-graded segment-entities to form the sub-based segment-entities. Figure 2 represents a sample evolution of different entities in the model.

[Insert Figure 2 here]

In road construction projects, often several trucks haul materials between material sources and job sites. These hauling trucks form other types of entity elements in the model, including aggregate material hauling truck-entity or water truck-entity. For each truck, the travel distance has to be calculated in order to estimate the travel time. Global model variables, accessible from different model elements, need to be set for tracking the project progress and the travel distance of the hauling truck-entities. Several types of road construction equipment, including loaders, dozer, roller compactors, and paving machines as well as material sources constitute resource elements in the model and participate in the model activities. For example, a loader loads soil into a truck, dozer levels dumped soil on a segment, a roller compactor compacts leveled soil on a segment, and a paving machine spreads asphalt on a road segment. The project duration, the total distance traveled by hauling trucks, the cost spent on road construction equipment, the cost spent on materials, and the wage paid to the crew are the main expected outputs of the model.

**Improvement Method**

Supplying materials from various available sources create a combinatorial problem in a road construction project. For instance, in a project with 5 different types of materials and 5 available sources for each, there will be 5^5 = 3125 different possible choices. Developing and running this number of DES models require too much effort and time, which is not acceptable in real road construction projects. In DES-based system improvement efforts usually several, not hundreds or even tens of, alternative solutions are modeled and compared, taking into account the main contributing factors. In this research, a two-round improvement approach is proposed to reduce the number of alternative scenarios while the main contributing factors are involved. In the first round, the improvement factors considered for developing material logistics scenarios include the managers' discretion, distance to the material sources, and material price. The material hauling distance and material price are considered due to their direct impacts on the material logistics cost. In order to take into account the manager's experience regarding other influential factors, a material logistics scenario was developed according to the project manager's advice. In each scenario, the same factor is accounted for selecting the material sources for different materials to limit the number of scenarios and avoid a combinatorial increase in the first round. Each scenario is evaluated using DES models. In the second improvement round, the procurement cost of each material is assessed in each scenario and the best logistics plan is identified for each material. The improved scenario is then formed from the combination of the best materials logistics plan identified for each material.

In the first improvement round, four types of scenarios are generated, taking into account the main contributing factors, as explained below:

1) Base scenario: The base scenario is formed according to the project managers' discretion. It is the original materials logistics plan developed by project managers. Material price and material supply distance are two main factors affecting the final material logistics cost. The impact of material price on the final cost of material logistics is simply calculable from the total cost of materials purchased. However, the impact of the material supply distance on the final cost depends on various factors. These factors include the operating cost of material handling equipment, maintenance cost of material handling equipment, equipment capacity, material arrival time, and even cost of onsite equipment and crew. The management team might develop this scenario based on one of the available analytical logistics planning techniques in the literature, or accordance with their collective experiences, project experts' input, and field constraints. In this scenario, they might choose a specific and unique combination of material price and distance. This scenario is evaluated and compared with other scenarios created in the first improvement round to incorporate the collective knowledge of the project management team.
2) Short-distance scenario: Travel distance is a driving factor for the improvement of the logistics plan. In this scenario, material sources with the shortest distance to the project job site are selected as the sources of material procurement. It should be noted that the job site location is dynamically changing over time as the project advances. The distances to the material sources depend on the job site location. Equation

1 represents the changing distance of material procurement from each material source. This equation is dynamically updated in the DES model of the road construction for every material source based on the project progress. The shortest distance source is identified accordingly. Material procurement is directed to the identified shortest distance source at each part of the road construction project. The price of materials is also taken into consideration in this scenario if more than one source of materials equally has the shortest distance to the job site. This scenario is generated in order to consider the situations where the distance is the main driving improvement factor. It should also be mentioned that the quality levels of different access roads can contribute to the hauling trucks' speeds and, consequently, to their travel time. Therefore, not necessarily the shortest distance represents the shortest time. Since a part of the road construction costs returns to the project duration, if the quality of the access roads is highly changing, scenarios based on the shortest travel time can also be considered.

3) Low-price scenario: In many situations, the price of materials is a key factor contributing to the final cost of material procurement. In this scenario, the sources with the lowest material prices are selected to supply the required materials. If more than one source of materials offers the lowest price, the distance could also be taken into consideration. This scenario is generated to identify the materials for which their prices are the main driver of their procurement process.

4) Combined low-price and short-distance scenarios: Multiple combinations of low-price and short-distance material supply can be adopted for creating combined scenarios. In this approach, low-price material sources within a specified distance to the job site are selected as the sources of material supply. In this perspective, multiple scenarios can be generated by deviating the distance limits. For example, in one scenario, the low-price material supply sources within 10 km distance to the job site can be selected. While another scenario can be generated by selecting the low-price material sources within 20 km distance. The adopted distances need to be set based on the congestion of material sources and the frequency of their distances to the job site. By use of the combined low-price and short-distance scenarios impacts of different levels of the material source price and distance are examined.

Figure 3 represents the above-mentioned explanation in the form of a diagram.

[Insert Figure 3 here]

The materials' logistics plans of the adopted scenarios in the first round are evaluated using the developed DES models of the road construction project. In the second improvement round, logistics plans of different types of procured materials are separately evaluated and compared for different adopted scenarios in the first improvement round. Then, the improved scenario is built by combining the logistics plans of different types of materials representing the best performance compared to the others. The improved scenario, built in the second round, is modeled and its performance is evaluated. It is expected that the improved scenario built in this round results in higher performance than the others since it incorporates the best results achieved in all other scenarios. In the end, the alternative material logistics scenario with the best performance among all generated scenarios in the first and the second round is selected. It should be noted that in every material logistics scenario, the policy adopted for each material, i.e., material price, supply distance, or a combined policy, stays constant for the entire project. However, the adopted policy for one material might be different in the improved scenario.

# CASE STUDY

To verify the applicability of the proposed method in a real-world project, it was applied to a 63.5-kilometer road construction project connecting Rafsanjan and Pariz in Kerman province, Iran. There were 28 potential material sources for six different types of materials used in the construction of the road. The total volume of the materials to handle was 1.1 million cubic meters. The materials were soil, base aggregate, water, bitumen, asphalt binder, and asphalt surface. Here, soil materials included sub-grade and sub-base aggregates. Since both of these soil materials were supplied from the same quarry, they were considered similar types of materials in the logistics plan improvement process.

In order to properly manage the project, the project team divided the implementation of the project into three main sections: Section 1 from km 0.00 to km 23.500, Section 2 from km 23.500 to km 43.500, and Section 3 from km 43.500 to km 63.500. To collect project specifications various project documents were reviewed, interviews were conducted, and direct operation observation and activity duration sampling were carried out by the research group. Interviews were conducted with the project manager, construction manager, and equipment maintenance manager all of whom had more than 15 years of experience in road construction projects. Figure 4 presents a schematic view of the project and relational locations of different material sources. The detailed information collected from various parts of the project and used as the input data and equations to the simulation model are presented in the Appendix. Tables A.1, A.2, A.3, and A.4 of the Appendix respectively present the statistical distribution of activity durations, the number of equipment, volumes, and equipment cost rates. The demanding nature of the road construction project necessitates specialized construction equipment to perform different activities. The uncertainties associated with the operation of road construction equipment operation have essential impacts on the distribution functions of activity durations presented in Table A.1. Many other uncertainties such as ground condition, weather condition, operators' skill, inflation, and the availability of financial sources can affect the project. The impacts of some of these uncertainties, such as ground condition, weather condition, and operator's skill, are also captured in the activity durations distribution functions presented in Table A.1. Nevertheless, some other uncertainties are not captured in the simulation model. Future studies can expand the proposed model to incorporate these uncertainties. In the following, the steps taken in the case study are explained.

[Insert Figure 4 here]

## First Improvement Round

Three scenarios were generated based on the first three directions provided in the first improvement round ("Improvement Method" Section), including the base scenario, the short-distance scenario, and the low-price scenario. Two combined scenarios were also generated by adopting two distance limits of 15 km and

30 km in consultation with the project management team. With this setting, Scenario 4 and Scenario 5 were formed for supplying materials from the low-price sources respectively within 15 km and 30 km distance. Table 1 summarizes the specifications of different scenarios generated for the first improvement round.

[Insert Table 1 here]

**DES Models Development**

DES models of the alternative road construction scenarios were developed following the modeling concepts explained in the "DES Model Development Steps" section with the collaboration of the engineering consulting company in charge of the project design. The developed models for different scenarios shared similar modeling logic. Only material hauling trips and the material price were adjusted in the models according to the specific condition of the adopted scenarios. The segment-entity in the developed models was set to one meter of the road. Detail specification of the activity durations, equipment fleet, earthmoving volumes, and equipment costs are presented in Tables A.1 to A.4 in Appendix. Figure 5, represents a view of the developed simulation model in AnyLogic. The model was developed at two levels, 1) top-level, which represents the main operations performed in the projects and, 2) submodel level, which details the material handling and system interactions within each operation. Figure 5 represents the top-level operation interactions in the project and the submodel level of the subbase construction operation to represent sample modeling elements used at the submodel level.

Face validity tests were performed by involving the project manager, job site superintendent, and several key crew members during the model development and model calibration processes. The sensitivity analysis was carried out on the developed DES models to test the legitimacy and validity of the achieved results in response to the deviations made to the model parameters (Banks et al., 2005, pp. 317). Hauling truck and roller compactor resources represented high utilization rates during the simulation model runs. The initial number of truck and roller compactor resources in the base scenario respectively was set to 17 and 10. As it was expected, an increase in the number of hauling truck and roller compactor resources reduced the project completion duration. The decrease in the number of these two resources increased the project completion duration correspondingly. Figure 6 presents the results achieved in this sensitivity analysis. The sensitivity analysis results demonstrate that when the number of roller compactors is equal to or less than 7 they become a bottleneck. In this situation, an increase in the number of other resources had no impact on the pace of the work and the number of roller compactors drove the pace. Here, all roller compactors were always busy, i.e., with 100% utilization, while other resources experience idle time and waiting for the progress made by the roller compactors.

[Insert Figure 5 here]

[Insert Figure 6 here]

Since the developed DES models in this research were subject to the randomness, result analysis and comparison were made based on the average values. According to Banks et al. (2005, pp. 348-349), with a standard deviation of 10.4 days for the operation duration of the base scenario, the confidence level of 95%, and the permissible error of 4 days, the required minimum number of iterations came to 26. To fulfill the required level of accuracy, the average of the results of 30 iterations was used for analysis and comparison of different material logistics scenarios. The average duration of 652 working days was achieved for the project completion of the base scenario. The project duration was estimated 650 working days in the original plan developed by the planning department, which shows conformity with the DES model developed for the base scenario. As it was expected, the shortest duration was achieved in the short-distance scenario, with an average duration of 641 working days. The longest duration was achieved for the low-price scenario, with an average duration of 744 working days.

**Second Improvement Round**

Table 2 presents the procurement cost of five different scenarios generated in the first improvement round. The procurement cost of materials includes material transportation cost, equipment maintenance cost, and material purchase cost as presented in Equations 2. This equation was used for calculating the procurement cost of each scenario using the collected project information, presented in the Appendix.

$$\text{Procurement Cost}(\$) = \sum_i \Big[ \Big( material\ handling\ equipment\ working\ hours_i (hour) * operating\ cost_i \left(\frac{\$}{hour}\right) \Big) + \Big( material\ handling\ equipment\ travel\ distance_i (km) * maintenance\ cost_i \left(\frac{\$}{km}\right) \Big) + \big( total\ purchase\ cost_i (\$) \big) \Big] \quad (2)$$

Where:
"i" represents $i^{th}$ material used in the road construction project

[Insert Table 2 here]

Deviations were seen in all material procurement costs in different scenarios. The highest cost deviation was seen in the soil material procurement cost with $307 Thousand difference between the least cost achieved in Scenario 1, or the base scenario, and the highest cost achieved in Scenario 3, or the low price scenario. The soil material had the highest number of alternative sources in the area with 12 different sources. The high deviation achieved in the soil material procurement cost might return to the increased number of the soil material supply sources. The procurement cost of the asphalt materials had the highest price in all scenarios. This high cost returns to the high asphalt price. According to the achieved results, Scenario 2 or the short-distance scenario in overall resulted in the least procurement cost for all required materials except the soil material. Scenario 1 or the base scenario represented the least procurement cost for the soil materials.

Therefore, Scenario 6 or the improved scenario was built by combining Scenarios 1 and Scenario 2 in the second improvement round. In Scenario 6, the logistics plan for all materials followed a short-distance source approach except for soil materials, which was set based on the project manager's discretion incorporating a combination of source distance and material price. The result achieved for Scenario 6 was compared with other scenarios developed in the first round. As expected, this scenario resulted in the least cost compared to all other five scenarios developed in the first improvement round with the total procurement cost of $10.58 Million. In fact, there was a potential cost reduction of $161 Thousand compared to the base scenario by adopting scenario 6. Scenario 6 also reduced $55 Thousand in procurement cost compared to Scenario 2, which was selected as the best scenario in the first improvement round. Although Scenario 6 scored the least overall material procurement and construction cost, its duration was one day more than Scenario 2. High deviations were also seen between equipment travel distances in different scenarios. As it was expected, hauling trucks scored the longest travel distance in all scenarios. The high deviation of 4 Million Km achieved for the hauling trucks in different scenarios represented the high impact of adopting different materials logistics plans on the travel distances. Here again, the equipment travel distance in Scenario 6 was slightly higher than the travel distance in Scenario 2. The cost-saving achieved in Scenario 6 compared to Scenario 2 mainly returns to the soil material cost. A comparison between different operational aspects of all six scenarios developed in two improvement rounds is presented in Table 3.

[Insert Table 3 here]

## Result Analysis

Achieved results showed that $161 Thousand or 1.5 percent of the related material logistics costs could be saved in the project by simply changing the material procurement sources from the base scenario to the improved scenario (Scenario 6). Here, the hauling distance worked as the dominant influential factor for procuring five materials including base aggregate, water, bitumen, asphalt binder, and asphalt surface. For soil material, however, the combined distance-price choice of project managers resulted in the lowest procurement cost. Table 4 compares the logistics plan for the base and improved scenarios.

[Insert Table 4 here]

Normally, project managers tend to work with a limited number of sources since the increased number of sources increases the managerial load of the project management team. However, a new set of material sources may become the most economical choices as the road construction project advances over time. Therefore, engaging various sets of material sources in the logistics plan is an expected characteristic of the improved scenario. Negotiation cost of procuring construction materials from alternative material sources is another cost that is not included in the proposed method. This additional cost should also be taken into account before finalizing the materials logistics plan.

# CONCLUSION

This research was motivated by the need for an appropriate method to plan material logistics of road construction projects. The dynamic and uncertain nature of the project job site and multiple influential operational factors involved make the materials logistics plan for road construction projects a complex problem. In the existing literature, this problem has been mainly dealt with analytical models. However, existing dynamics and uncertainty in construction operations are difficult to capture using analytical methods. This constraint limits the ability of analytical methods to properly capture the complexity involved in the construction operations and reduces their performance. In this research, a novel method that leverages the capabilities of DES to incorporate uncertain, dynamic, and complex operational details specific to the logistics planning problem in the road construction project context was proposed. This method facilitates the evaluation and improvement of materials logistics plans in road construction projects. Reduced overall material procurement cost is the expected implication of using the proposed method in road construction projects. The academic contributions of this research come in two folds: 1) a simulation-based method was introduced for capturing the existing complexity issue in the materials logistics plan problem in the road construction project context, and 2) a novel heuristic two-round improvement method was proposed to overcome the existing combinatorial issue of the materials logistics plan. Besides, the successful application of the proposed method in a real 63.5 km road construction project in Kerman province, Iran, demonstrated the applicability of the proposed method in practice.

The proposed method is subject to limitations. By its nature, the proposed heuristic method does not guarantee a globally optimized material logistics plan. There is an opportunity for future studies to focus on the development of meta-heuristic methods combined with the proposed simulation-based method to find quasi-optimized plans. Deviations in the quality of the access roads and their impact on the operating and maintenance cost of equipment have not been considered in the developed model. Incorporating the quality of access roads in future work can improve the outcome. The need for time-consuming and resource-intensive data collection is another limitation of the proposed DES-based method that might discourage practitioners in applying the method in practice. However, recent advances in automated data collection technologies can alleviate this issue and indicate signs for the future expansion of DES applications. Future research can focus on linking the automated data collection schemes with the proposed simulation models to address this issue. DES technique applied in this research can be augmented by other simulation-based techniques such as system dynamics and agent-based simulation to incorporate the behavioral, environmental, and social influential factors and improve the model accuracy. The proposed method can be adopted in other linear projects, such as pipeline construction and tunneling projects, where job site location moves over time and multiple material sources are available.

# APPENDIX

Information collected from different parts of the 63.5 km road construction project in Kerman Province, Iran.

**Table A.1.** Activity durations distribution functions based on the goodness of fit of sample durations

| Number | Activity | Duration/ Progress Rate Function | Explanation |
|---|---|---|---|
| **1** | Dumping truck | Chi-Squared(v=1) (min) | Aggregate operation |
| **2** | Loading truck | Rayleigh(s=3.6384) (min) | Aggregate operation |
| **3** | Truck speed with load | Chi-Squared(v=47) (km/h) | Aggregate operation |
| **4** | Truck speed without load | Chi-Squared(v=60) (km/h) | Aggregate operation |
| **5** | Dumping truck | Exponential ($Lamda$=0.21053) (min) | Asphalt operation |
| **6** | Loading truck | Beta (a1=0.74657 a2=1.0941 a=10.5 b=16.8) (min) | Asphalt operation |
| **7** | Truck speed with load | Rayleigh(s=72.239) (km/h) | Asphalt operation |
| **8** | Truck speed without load | Uniform (a=75.206 b=104.33) (km/h) | Asphalt operation |
| **9** | Spray sprinkler | Beta ($a_1$=0.50726 $a_2$=1.1356 a=25 b=132) (min) | |
| **10** | Loading sprinkler | Exponential ($Lamda$= 0.03112) (km/h) | |
| **11** | Sprinkler speed with load | Gamma (α=47.183 β=0.72272) (min) | |
| **12** | Sprinkler speed without load | Exponential ($Lamda$=0.02317) (km/h) | |
| **13** | Roller compactor | Normal(σ=0.46288 μ=1.0077) (h) | Service to one truckload |
| **14** | Spread grader | Normal(σ=6.8813 μ=10.258) (h) | Service to one truckload |

**Table A.2.** Number of equipment allocated to different project sites

| | Machine name | Site 1 | Site 2-before Site 1 completion | Site 2- after Site 1 completion | Site 3- before Site 2 completion | Site 3- after Site 2 completion |
|---|---|---|---|---|---|---|
| **1** | Truck | 15 | 8 | 23 | 9 | 32 |
| **2** | Sprinkler | 3 | 3 | 6 | 2 | 8 |
| **3** | Bitumen sprayer | 1 | 0 | 1 | 0 | 1 |
| **4** | Grader | 5 | 2 | 2 | 2 | 2 |
| **5** | Excavator | 2 | 2 | 2 | 5 | 5 |
| **6** | Dozer | 2 | 2 | 2 | 1 | 1 |
| **7** | Roller compactor | 10 | 4 | 14 | 6 | 20 |
| **8** | Asphalt Compactor | 2 | 0 | 2 | 0 | 2 |
| **9** | Finisher | 1 | 0 | 1 | 0 | 1 |

**Table A.3.** The main volumes of the project

| Material | Volume |
|---|---|
| Excavation | 2,0,32,923 $m^3$ |
| Soil | 1,254,389 $m^3$ |
| Base aggregate | 121,900 $m^3$ |
| Asphalt Binder | 86,414 $m^3$ |
| Asphalt surface | 12,217 $m^3$ |

**Table A.4.** Equipment cost

| | Equipment | Operating cost ($ / hour) | Maintenance* ($ / 1000 km) |
|---|---|---|---|
| **1** | Truck | 5.1 | 83.6 |
| **2** | Sprinkler | 4.3 | 65.5 |
| **3** | Bitumen sprayer | 12.4 | 51.7 |
| **4** | Grader | 17.6 | - |
| **5** | Excavator | 17.6 | - |
| **6** | Dozer | 32.4 | - |
| **7** | Roller compactor | 4.9 | - |
| **8** | Asphalt Compactor | 8.1 | - |
| **9** | Finisher | 27.0 | - |

* The maintenance cost of equipment is considered dependent on the travel distance, for the equipment, not participated in the material procurement, constant travel distance is considered and its maintenance cost is not accounted as a contributing factor to the logistics plan decision.

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**Table 1.** Alternative scenarios

| Scenario No. | Description |
|---|---|
| Scenario 1 | Base scenario, project management's plan |
| Scenario 2 | Supply with short-distance source |
| Scenario 3 | Supply with low-price source |
| Scenario 4 | Supply with the low-price source within 15 km |
| Scenario 5 | Supply with the low-price source within 30 km |

**Table 2.** Procurement cost achieved for different scenarios in the first improvement round

| Item | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|---|---|---|---|---|---|
| **Soil procurement cost (T$*)** | **540.1** | 600.8 | 846.8 | 699.0 | 762.8 |
| **Base aggregate procurement cost (T$)** | 359.2 | **330.1** | 420.5 | 368.0 | 370.4 |
| **Water procurement cost (T$)** | 29.7 | **29.7** | 32.9 | 34.2 | 33.3 |
| **Bitumen procurement cost (T$)** | 19.4 | **10.8** | 12.2 | 19.5 | 19.6 |
| **Asphalt binder procurement cost (T$)** | 3374.2 | **3331.9** | 3378.3 | 3367.5 | 3342.3 |
| **Asphalt surface procurement cost (T$)** | 691.0 | **681.5** | 691.0 | 688.8 | 683.6 |

* Thousand US dollar

**Table 3.** Operational results achieved in different scenarios

| Item | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|---|---|---|---|---|---|---|
| **Material procurement and construction cost* (Million US $)** | 10.74 | 10.63 | 11.76 | 11.38 | 11.40 | **10.58** |
| **Duration (Day)** | 652 | 641 | 744 | 719 | 717 | 642 |
| **Material hauling truck travel distance** (Thousand Km)** | 4844 | 3399 | 7314 | 4742 | 5144 | 3634 |
| **Sprinkler Travel Distance (Thousand Km)** | 55.1 | 50.8 | 94.4 | 55.1 | 76.4 | 50.8 |
| **Bitumen Sprayer Travel Distance (Km)** | 12.6 | 6.1 | 6.1 | 12.6 | 12.6 | 6.1 |

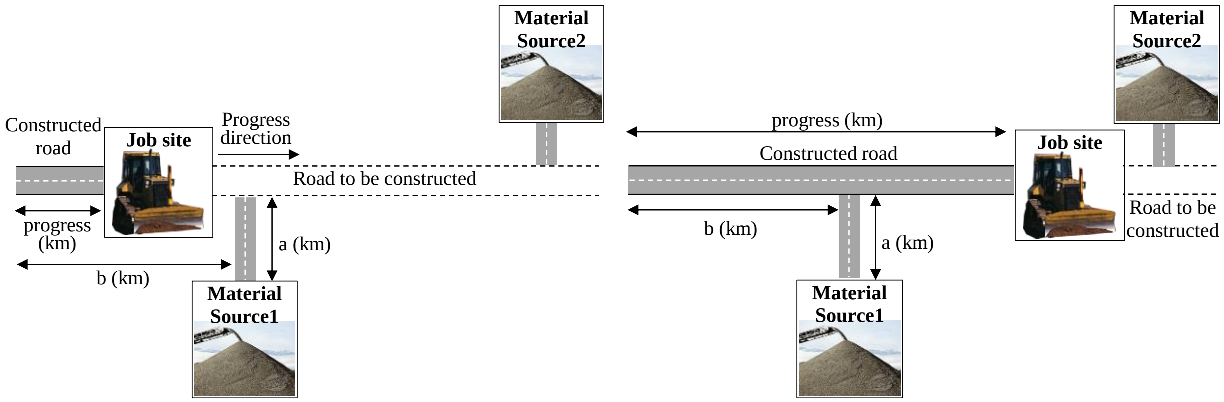
* Purchase cost of bitumen is excluded from material procurement cost since its price is constant in all of its sources and does not contribute to the final logistics plan decision.

**Includes hauling distance of soil, base aggregate, asphalt binder, and asphalt surface materials.

**Table 4.** Logistics plan for the base and the improved scenarios

| Item | Scenario 1 (Base scenario)* | Scenario 6 (improved scenario)* |
|---|---|---|
| **Soil procurement** | **km 0.00 to km 18.00:** Source A8<br>**km 18.00 to km 22.00:** Source A7<br>**km 22.00 to km 48.00:** Source A5<br>**km 48.00 to km 63.50:** Source A1 | **km 0.00 to km 18.00:** Source A8<br>**km 18.00 to km 22.00:** Source A7<br>**km 22.00 to km 48.00:** Source A5<br>**km 48.00 to km 63.50:** Source A1 |
| **Base aggregate procurement** | **km 0.00 to km 18.00:** Source B3<br>**km 18.00 to km 63.50:** Source B2 | **km 0.00 to km 14.90:** Source B4<br>**km 14.90 to km 43.60:** Source B3<br>**km 43.60 to km 50.25:** Source B2<br>**km 50.25 to km 63.50:** Source B1 |
| **Water procurement** | **km 0.00 to km 20.00:** Source C5<br>**km 20.00 to km 28.00:** Source C3<br>**km 28.00 to km 54.00:** Source C2<br>**km 54.00 to km 63.50:** Source C1 | **km 0.00 to km 12.85:** Source C5<br>**km 12.85 to km 27.00:** Source C4<br>**km 27.00 to km 37.75:** Source C3<br>**km 37.75 to km 50.00:** Source C2<br>**km 50.00 to km 63.50:** Source C1 |
| **Bitumen procurement** | **km 0.00 to km 63.50:** Source D4 | **km 0.00 to km 34.48:** Source D4<br>**km 34.48 to km 63.50:** Source D2 |
| **Asphalt binder procurement** | **km 0.00 to km 23.00:** Source D4<br>**km 23.00 to km 27.00:** Source D2<br>**km 27.00 to km 38.00:** Source D4<br>**km 38.00 to km 54.00:** Source D2<br>**km 54.00 to km 63.50:** Source D4 | **km 0.00 to km 34.48:** Source D4<br>**km 34.48 to km 63.50:** Source D2 |
| **Asphalt surface procurement** | **km 0.00 to km 63.50:** Source D4 | **km 0.00 to km 34.48:** Source D4<br>**km 34.48 to km 63.50:** Source D2 |

* Sources codes follow the Sources codes represented in Figure 4.




a) Early stages of the road construction b) Latter stages of road construction

**Figure 1.** Distance change for source locations during a road construction project

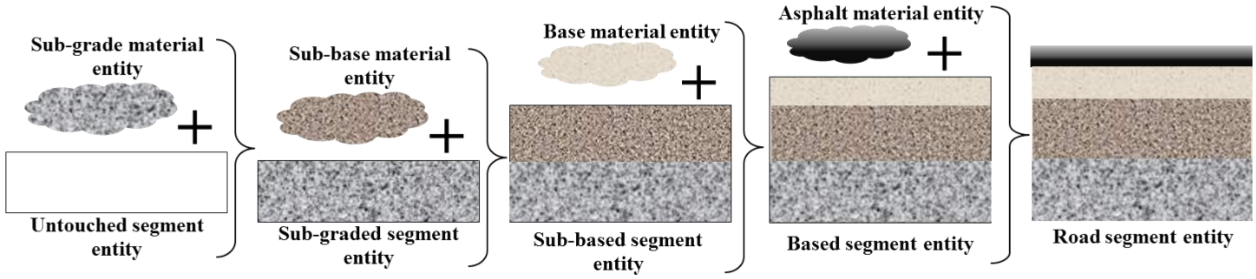



**Figure 2.** A sample evolution stages of a segment entity during a road construction project

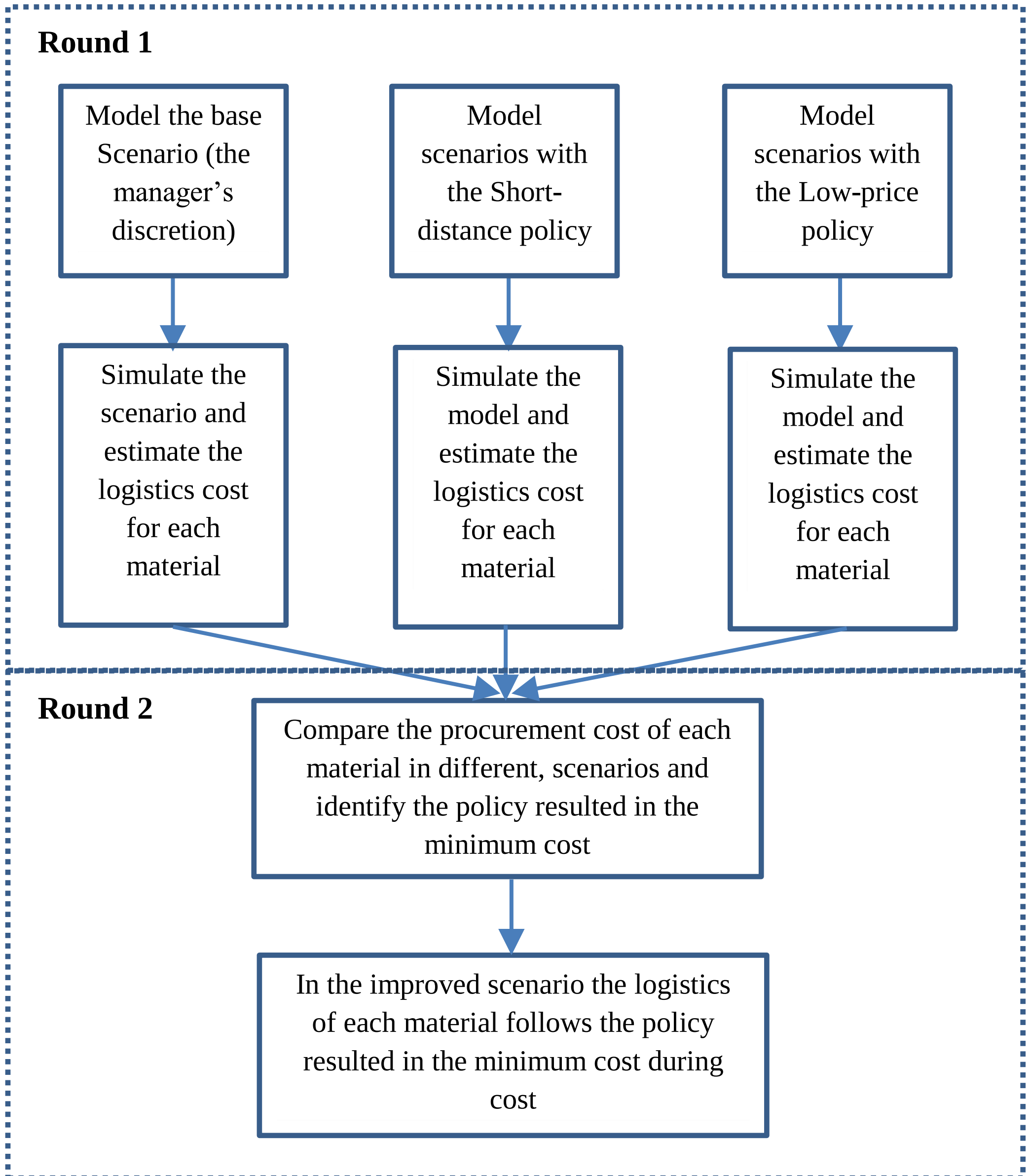



**Figure 3.** Different steps of the proposed two-round simulation-based improvement

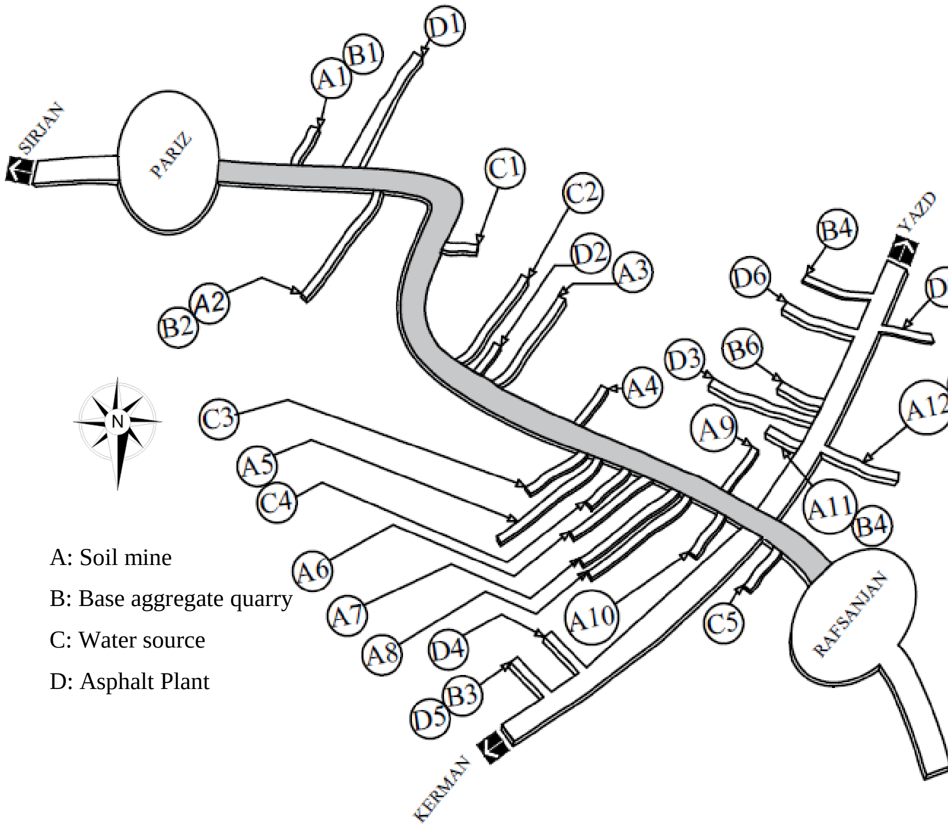



**Figure 4.** Overall view of the project and material source locations

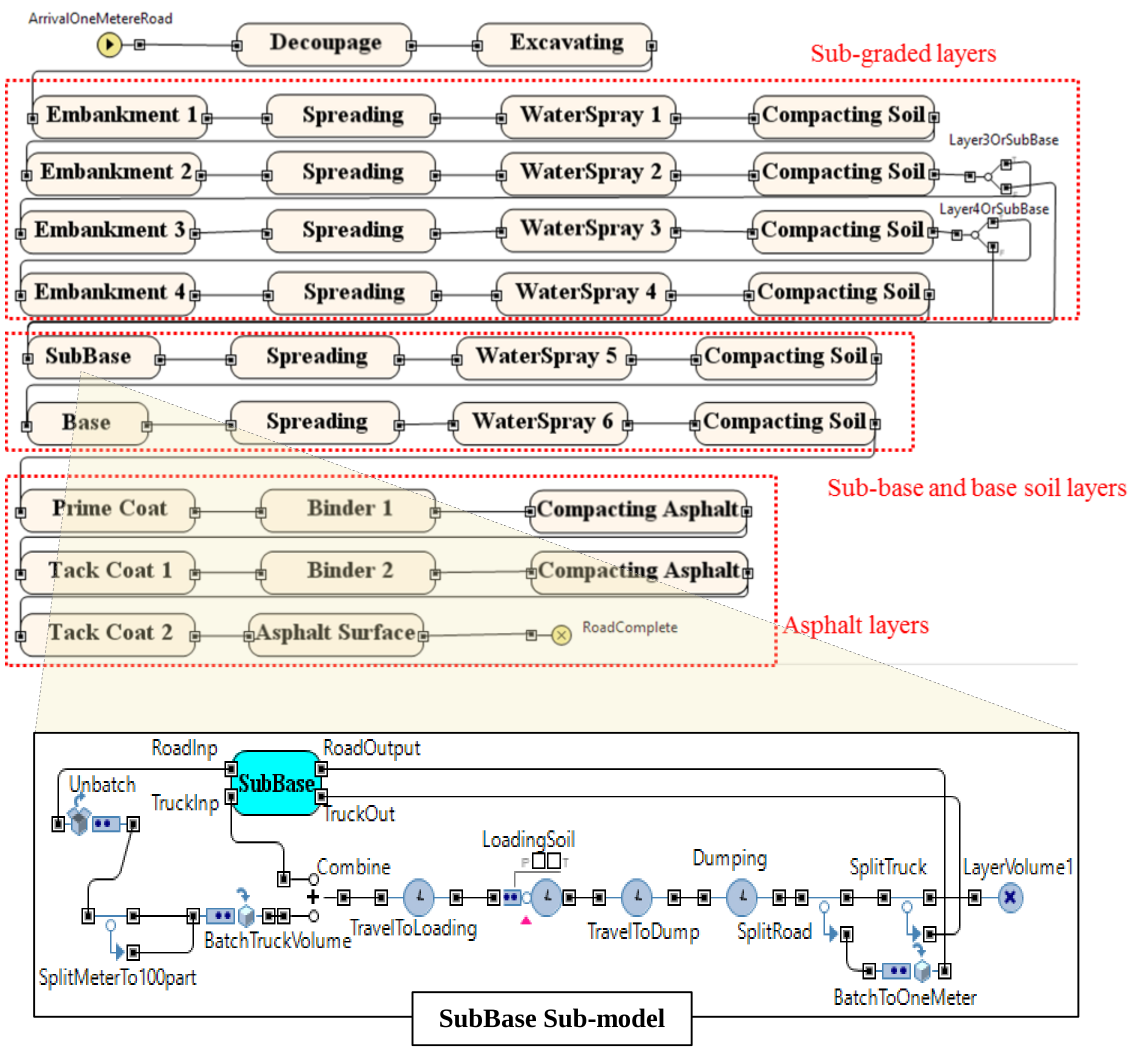
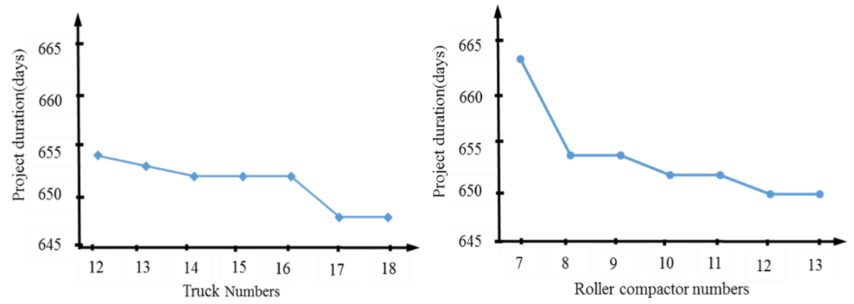



**Figure 5.** A view of the developed simulation model




a. Changing truck numbers b. Changing roller compactor numbers

**Figure 6.** Sensitivity analysis results achieved for hauling trucks and roller compactor