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Evaluation of Agent-Based and Discrete-Event Simulation for Modeling Construction Earthmoving Operations

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ABSTRACT

One of the most common operations to any construction project is earthwork. In fact, most, if not all, construction projects begin with earthwork activities. These activities require heavy equipment, are generally quite costly and consume a considerable amount of time. On another hand, the construction industry is becoming increasingly competitive over the years, whereby the need to continuously find ways to improve construction performance. In order to address the aforementioned adversities, this paper takes the initial steps and presents work targeted at efficiently managing logistics of earthwork operations in the construction field, namely cut and fill processes, and hauling activities. This dynamic and complex problem, which entails a lot of parameters and variables, is addressed in detail through creating two simulation models, a Discrete-Event Simulation (DES) model and an Agent-Based Simulation (ABS) one, using the multi-method simulation software AnyLogic 7.1. The purpose behind this study is two-fold: (1) capturing and visualizing the interaction among the different resources or entities in an earthmoving operation and defining the weak links in order to improve the efficiency of such activities onsite, and (2) comparing DES and ABS approaches and evaluating the advantages and drawbacks of each when modeling earthmoving operations. Results of both approaches are presented and analyzed with regard to improving performance of earthmoving operations, followed by a discussion of the application and effectiveness of using each of the presented simulation approaches in modeling construction activities.

Keywords -

Construction Management; Simulation Modeling; Discrete-Event Simulation, Agent-Based Modeling; Earthwork;

1 Introduction

Information Computer Technology (ICT) tools have been increasingly developing which is enhancing their use in the field of construction. For instance, simulation modeling and visualization are often used at the stage of planning to improve construction performance and efficiency. Different types of simulation approaches have been used to mimic construction operations among which Discrete Event Simulation (DES) ranks as the most widely used one. A newer simulation approach, Agent Based Modeling (ABM), emerged later in the 1990s. In construction, one of the most common and expensive activities to any project is earthwork operations, which explains the necessity of simulating and analyzing such processes which provides insight to achieve cost savings and higher operation efficiency.

Previous research efforts aimed at comparing DES and ABM in different fields such as Operations Research and the implementation of new management policies. These studies conclude that each simulation modeling type has its advantages and its disadvantages and selecting a type should depend on the problem and scenario modeled [1] [2] [3]. Other studies have focused on modeling earthwork operations using DES approach [4] [5]. As for ABM, although it is still not widely used in construction, some papers used it to study construction labor productivity on site [6], to estimate the productivity of bored piles [7], or even to model earthmoving operations [8]. However, in the case of the latter, the model focused mainly on managing logistics, spatial time clashes and safety.

In this paper, two models are created to simulate earthwork operations, one following the discrete-event method and the other using ABM approach. The two models are accompanied with a 3D animation for validation purposes and are tested on a case study to compare the results. Then, the advantages and disadvantages of each simulation approach are highlighted with respect to earthwork operations. Finally, the potential of combining both approaches into a multi-method model is discussed.

2 Methodology

In order to achieve the paper's objective, the methodology is divided into two main parts. The first part consists of defining earthwork operations by listing the activities involved in this process and by determining the resources required for each activity as well as the activities' daily outputs. The second part includes the design of two simulation models of earthwork activities, one of which is a discrete-event simulation model while the other one is agent-based. Both models are modeled using AnyLogic 7.1 and accompanied by a 3D animation.

2.1 Construction Process Description

Earthwork operations in the scope of this research work mainly refer to cut and fill activities. In fact, these activities are commonly performed prior to road construction so that the earth where the road alignment will be passing matches the road width and slopes as per the design. The activities involved in the process are excavating, filling and hauling (empty and full). The resources required are at least one of each of the following: excavator, loader and truck. The excavator excavates the cut areas while the loader fills the fill areas. The former dumps the cut soil into the truck while the loader uses the soil brought by the truck to fill the earth where necessary. So the trucks would be going back and forth from the excavator to the loader and would have to spend time waiting when there are more trucks than earthwork equipment can handle. As for the case where there are fewer trucks than what the excavator or loader can accommodate, the latter equipment would be sitting idle on site which would lead to money waste due to inefficient resource allocation. Another case that needs to be highlighted is the case when cut and fill quantities are not equal. If cut volume is greater than fill volume, the additional cut needs to be transported to a certain specified dump location depending on the project. As for the second option, when fill volume is greater than cut volume, borrow needs to be brought to site to cover the remaining volume of fill. In that case, an additional activity is required which is loading borrow to trucks. This activity involves the excavator loading borrow volumes into the empty trucks.

According to the RS Means Building Construction Cost Data book [9], the daily outputs of the previously mentioned activities are as shown in Table 1. The field daily output for hauling activities is empty because these activities do not have a daily output. The measures that represent their productivities are the truck's speed and capacity. The truck capacity is considered to be 9 m³ and the speed 32 km/h. The same speed is assumed

for the other vehicles as well.

Table 1 Activities' Resources and Daily Outputs

Activity	Resource	Daily Output
Excavating	Dozer (410 HP)	489 bank m ³
Filling	Dozer (200 HP)	765 loose m ³
Hauling Full	Dump Truck	-
Hauling Empty	Dump Truck	-
Loading Borrow	Dozer (200 HP)	917 loose m ³

2.2 Simulation Models

Simulation modeling and visualization are increasingly used tools in the field of construction. Simulation modeling consists of creating a model that is the "imitation of the operation of a real-world process or system over time" [10]. It takes data from the model creator, as input, based on historical data and assumptions. The model itself consists of logical relationships and processes defined by the modeler. The output consists of results based on the interaction of the input data with the designed model. In most cases, it is useful to accompany a simulation model with visuals to provide the viewers with an animation of the process being simulated. Visualization can serve as a validation tool [11] and can aid viewers that are unfamiliar with simulation to understand the modeled process. Additionally, there are different types of simulation. The three main types are discrete-event, agent-based and system dynamics. In this research, the first two were used and are defined more thoroughly in the following sections.

2.2.1 Discrete-Event Simulation Model

Discrete-Event simulation modeling also, referred to as "Process-Centric" in AnyLogic, consists of dividing a continuous process into discrete parts to simplify analysis [12]. The process in question is modeled as a sequence of discrete events or activities. Entities arrive into the model at a certain arrival rate and go through its activities one at a time sequentially. The AnyLogic elements used in modeling the earthwork operations are the source, service, resource pool, sink, seize, release and select output. The source generates the entities that flow in the process; the service represents each of the activities and delays the entities while requiring resources from the resource pools; the sink is where the entities are disposed; the seize and release elements bring and remove resources from the process; and the select output is used when there are two alternative paths to choose from. Based on the aforementioned elements, Figure 1 depicts the earthwork operations DES model.

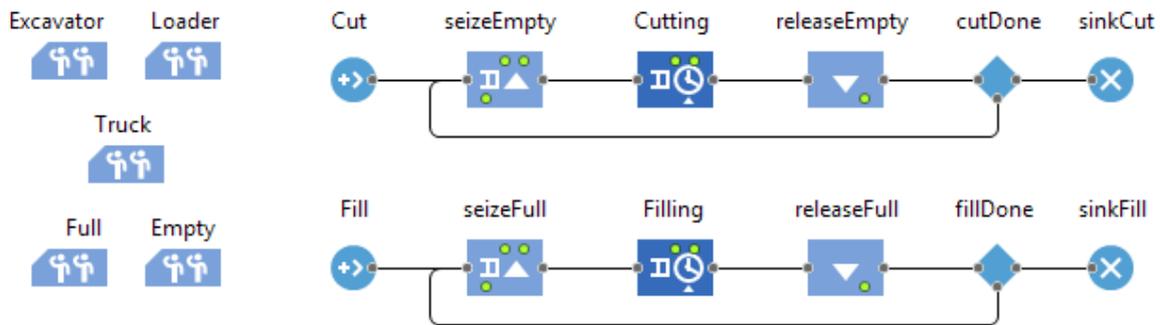


Figure 1. Earthwork Operations Discrete Event Simulation Model

As shown in Figure 1, two sources (“Cut” and “Fill”) are used to model respectively the cut and the fill quantities. Each generated entity represents 9 m³ to be cut or to be filled, which is the truck capacity. “Cutting” and “Filling” are service elements which represent the activities referred by their names. Their main properties are the resources required for execution and the delay time per entity. The resources required by “Cutting” are “Excavator” and “Truck”, and those required by “Filling” are “Loader” and “Truck”. As for the delay times, given that an entity represents 9 m³ and given the daily outputs shown in Table 1, the delay time for cutting is thus 0.147 hours per entity, for filling 0.094 and for loading borrow 0.078. To model loading borrow, the delay time of cutting is defined dynamically by the following expression:

```
Cutting.in.count() > N ? 0.078 : 0.147
```

In the above expression, N represents the quantity of cut above which the use of borrow will be necessary and thus the excavator will no longer be cutting, instead it will be loading borrow onto the truck which is done at a different rate.

“sinkCut” and “sinkFill” are simply where the entities are disposed. Although there is one type of truck in the process, this resource can serve different purposes whether empty or full, which is why it is important to discern between these two instances. To model that idea, two resource pools were added: “Empty” and “Full”. Those are seized right before the start of the activity to ensure that there is actually an empty truck for cutting or a full one for filling. As such, no truck is seized by the activities unless the condition of whether it’s full or empty is satisfied. Once the activities are completed, all resources are released which explains the presence of release elements right before the sinks.

An important difference needs to be highlighted when it comes to defining the number of resources is for the distinct pools. In fact, the number of excavators, loaders and trucks is a static value defined at the

beginning of the simulation run and kept constant throughout the simulation period. As for the Empty and Full resources, their number varies dynamically during the run. Initially, at the start of the earthmoving process, Full is equal to zero while Empty is equal to the number of trucks. This reflects the fact that at the start of the process, all trucks are empty. However, these numbers vary dynamically as the process is being executed. Two variables are added to represent the quantity of each of these two resources and are called “EmptyNb” and “FullNb” respectively. After each time “Cutting” is executed and all resources are released, the following code is executed:

```
FullNb++;
EmptyNb--;
Full.set_capacity(FullNb);
Empty.set_capacity(EmptyNb);
```

The above means that the variable representing the number of “Full” resources is increased by one, while the variable representing the number of “Empty” resources is decreased by one to reflect that a truck has been filled. Then, the resource pool’s number of units is adjusted accordingly using the function “set_capacity”. A similar code is executed after the execution of Filling where the only difference is that FullNb is decreased by one, while EmptyNb is increased by one to reflect that a truck has been emptied.

The select output elements named “cutDone” and “fillDone” do not contribute to the process logic. However, their role is to improve the efficiency of the model runs. In fact, since entities represent 9 m³, it is most likely that the number of entities will be huge in case the model is applied on large projects. To that end, each entity will be used more than once instead of producing additional ones. Each entity is assigned a variable called counter which stores the number of times the entity has been used in the process. At the select output element, if counter is less than 10 (initially equal to 0), it is sent back to the process and counter is

increased by one, otherwise, if equal to 10, which means that it has already passed 10 times in the process, it is discharged in the sink..

After the model logic has been defined, the visualization needs to be created. The latter would be done using AnyLogic's *space markup* library which includes nodes used to define the different entities' and resources' movements. In this model, rectangular nodes are used to represent the different road segments. To make things easier and more user-friendly, these road segments i.e. rectangular nodes are created dynamically using as input an MS Excel file that can be prepared by the user. The data file used in the presented model is shown in Table 2 filled with hypothetical data (actual data are calculated in the case study). The quantity represents the amount of soil to be either cut or filled depending on the type. X and Y are the coordinates of the top right corner of the segments.

Table 2 Sample of Road Segments Data

ID	Type	Quantity (m ³)	X (m)	Y (m)	Width (m)	Height (m)
1	cut	2448	0	0	12.3	75
2	fill	2195	0	75	12.3	265
3	cut	5261	0	340	12.3	410
4	fill	230	0	750	12.3	150

On startup of each run, a code is executed, the purpose of which is to create road segments based on the MS Excel input by the user depending on the case study. Then, based on the quantities, the entities which represent 9 m³ of cut or fill are spread according to the table in their respective segments. For the resources (except for Empty and Full), the option "Send seized resources to entity" is selected. As such, the resources will be moving to the different required road segments during execution. Finally, to complete the animation, 3D shapes are assigned to the truck, excavator and loader. The appearance can be further improved by adding colors and textures to the road segments and the background.

Lastly, and to improve the user-friendliness of the model, edit-boxes are added. These can be filled by the user to specify the number of each of the resources as shown in Figure 2.

Excavator(s)	<input type="text" value="3"/>
Loader(s)	<input type="text" value="2"/>
Truck(s)	<input type="text" value="5"/>

Figure 2. Edit-Boxes to Be Filled by User

2.2.2 Agent-Based Simulation Model

The same model is recreated, only this time, using Agent-Based Modeling (ABM). ABM is an essentially decentralized and individual-centric approach. When designing an agent based model the modeler identifies the active entities or agents (which can be people, companies, assets, vehicles, etc.), defines their behavior, puts them in a certain environment, establishes connections between them, and runs the simulation. The global behavior then emerges as a result of interactions of distinct individual behaviors [12].

The main building blocks of ABM are state-charts. Those are mainly composed of states which are linked by transitions. They are used to represent the possible states of an agent and to define the relationships between them. The first step in any AB model is to start by identifying the different agents. In the earthwork operations model, the defined agent types are: Road Segment, Excavator, Loader and Truck.

The agent Road Segment has two parameters and one variable: IsCut, Quantity and counter, all of integer type. When IsCut takes the value 1, it means that the corresponding road segment is of type cut while a value of 0 means fill. Quantity represents the quantity of soil to be either cut or filled for each segment. The variable counter is used to monitor the progress of each road segment. Moreover, a shape is assigned to this agent which is a rectangle, the position and size of which are defined dynamically. Similarly to the DES model, this data is input to the model using an MS Excel file including a table similar to Table 2. At startup, the road segments are positioned according to the input coordinates and dimensions. The state-chart for the agents of type Road Segment is shown in Figure 3. Figure 4 and Figure 5 show the state charts of the excavators and trucks respectively. No figure was added for the state-chart of the loader because it is very similar to that of the excavator.

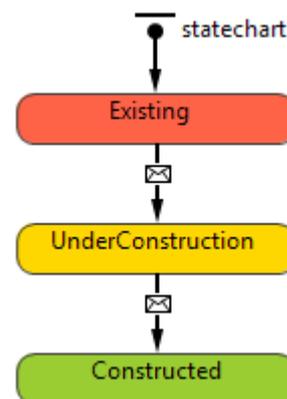


Figure 3. Road Segment State Chart

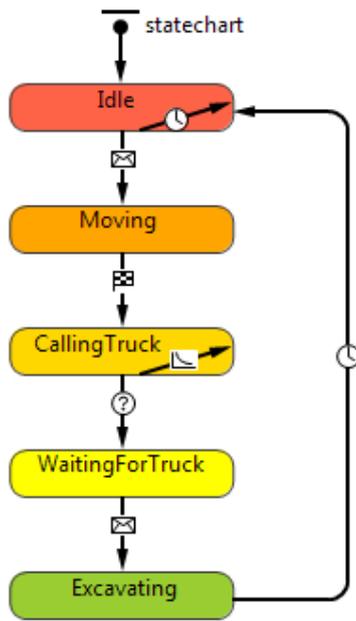


Figure 4. Excavator State Chart

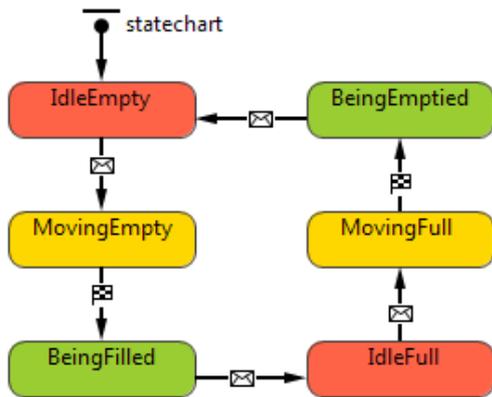


Figure 5. Truck State Chart

Different types of transitions to go from a state to another exist in AnyLogic. Those marked by a clock are timeout transitions which occur after a certain specified time. Those labeled with a question mark occur when a specified condition is true. As for the links marked with an envelope, they happen when a particular message is received. The ones with a flag take place on the arrival of a moving agent to its destination. Finally, the transitions marked by a graph are based on a specified rate. Now that the transitions are explained, it is possible to further elaborate on the different agents' state-charts defined in the model.

Initially, road segments are in the state *Existing*, loaders and excavators in the state *Idle* and trucks in the state *IdleEmpty*. The first action to happen is through the internal transition triggered by timeout in the

excavator and loader's state-charts, specifically in the *Idle* state. An internal transition does not cause a change in states, it simply triggers an action. The timeout is assigned to be one second. The action is the execution of a function that evaluates all road segments to check whether they are cut segments and then compares their variable counter to their quantity parameter. If the two are equal, it means that the road segment has been fully completed, if not a message is sent to the excavator and the variable counter is increased by one to reflect that an excavator has already been sent to that specific road segment. In addition to that, the sent message triggers the subsequent transition which changes the excavator's state into moving at which the vehicle is ordered to move to the concerned road segment. The similar logic applies to the loader.

Once the excavator or loader arrives to the segment, a message is sent to the road segment to change its state from *Existing* to *UnderConstruction* and the vehicle automatically becomes in the state *CallingTruck*. This state is essential to have because it allows the excavator or loader to check whether there is an available truck to send a message to, and if not, the model would yield an error saying that the message is being sent to null. The internal transition in the *CallingTruck* state repeatedly calls a function that evaluates whether there are trucks in the state *IdleEmpty* for the case of the excavator or *IdleFull* for the case of the loader. If so, the nearest truck is called and the excavator/loader moves to the state *WaitingForTruck* and sends a message to the nearest idle truck which would thus start moving towards it. Once it arrives to the vehicle that called it, it becomes in the state *BeingFilled* or *BeingEmptied* depending on the equipment that called it, while the latter moves to the state of either *Excavating* or *Filling*.

Finally, the transition that causes the excavator or loader to move from that last state to *Idle* is a timeout transition with a duration equal to the time required to excavate or fill 9 m^3 . Once this period is over, two messages are sent: one to the truck to change its state to either *IdleFull* or *IdleEmpty* (depending on whether it is leaving the excavator or the loader); and the other message is sent to the road segment to change its state from *UnderConstruction* to *Constructed*.

The interaction between these different state-charts results in a simulation model representing earthmoving operations.

3 Case Study and Results

In order to test the created models, it is essential to select a case study where the models are applicable. It is important to accompany simulation models with actual case studies to validate the models and to assess their effectiveness and usefulness.

3.1 Case Study Description

In a parallel study, the construction process of a potential on-shore wind farm in Marjeyoun, Lebanon, is being planned, simulated, visualized and optimized. This process includes the construction of a relatively big road network between the wind turbines. To complete the road network construction, a high amount of cut and fill operations need to be performed which is why this particular case study was selected. The project includes 30 wind turbines which are interconnected by a road network of length 14 km approximately. The turbines are shown as yellow dots and the road is shown in black lines in Figure 6.

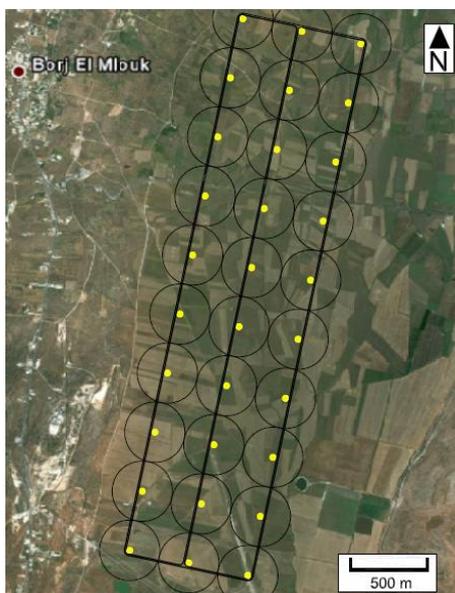


Figure 6. Case Study Road Network Layout

The road design was performed based on the above horizontal alignment. The specifications of the design, done in a parallel study, are shown in Table 3, and the road section is shown in Figure 7.

Criteria	Value
Minimum turning radius	32 m
Minimum longitudinal radius	200 m
Maximum longitudinal slope	10%

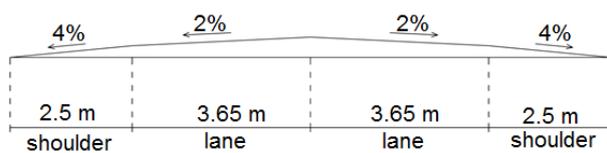


Figure 7. Road Cross Section

Based on the road design described above, it was determined that 60,416 m³ of soil need to be cut versus an amount of 171,309 m³ to be filled. Therefore, there is a need for 110,893 m³ of borrow on site to cover the amount of fill that cannot be covered by the excavated quantity.

3.2 Results and Evaluation

Following the quantity calculations of the case study, mainly cut and fill quantities, these numbers can now be used as inputs for the simulation models. The other required inputs are the number of each resource type. Since the truck is the most critical resource type taking different states (i.e. empty or full) and required for both cut and fill activities, it is our main considered factor. Therefore, and in order to test and assess the model, the number of excavators and loaders is kept fixed while the number of trucks is varied to evaluate the effect of the number of trucks on project duration.

Before analyzing results, an important step is to verify and validate the models, and one tool to perform that would be visualization [11]. As such, the models are run and the visualization is observed to see whether the behaviour reflects the desired and the actual process. In fact, the 3D animations generated confirmed that both models generate the required result. Figure 8 presents a snapshot of 3D visualization.

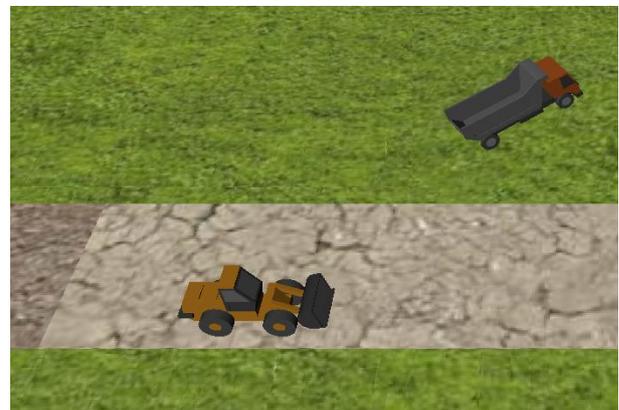


Figure 8. Simulation and Visualization Output

Now that the model has been verified to a certain extent through the animation, the results shall be evaluated. In fact, using parameters variation experiment type provided by AnyLogic software, the DES and the AB models are run respectively with the number of trucks varied between 1 and 10 with an increment of 1. The output is the duration of the whole project in working hours. The number of excavators and loaders was chosen to be a fixed value equal to six for

each of the two resources. Table 4 presents the output results for both the DES and AB model.

Number of Trucks	Duration (hours)		% variation
	DES	ABM	
1	4,827	4,790	0.77%
2	2,415	2,395	0.83%
3	1,610	1,597	0.84%
4	1,207	1,198	0.75%
5	966	958	0.82%
6	805	799	0.81%
7	690	685	0.75%
8	604	599	0.79%
9	538	533	0.92%
10	486	480	1.15%

The first step in analyzing the results is comparing whether both types of modeling yielded the same results. As shown in Table 4, for trucks between 1 and 10, the largest percentage variation was for 10 trucks and was equal to 1.15% which is negligible. For the rest of the cases, the variation in the project duration between the DES and the AB models did not exceed 1%. These numbers show that both modeling approaches yielded very similar results.

Moreover, given that both models resulted in similar durations, Figure 9 presents the average project durations of the two models versus the number of trucks in a graph to further analyze the effect of varying the number of trucks on the total project duration.

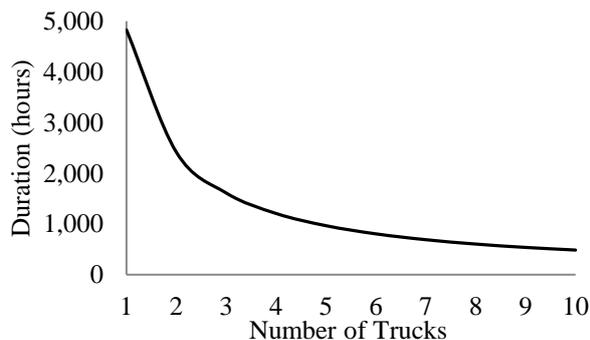


Figure 9. Average duration versus number of trucks

Based on Figure 9, as expected, it is clear that the duration decreases with a higher number of trucks. Not only does the duration decrease, but the rate at which it is decreasing declines as well. This is also expected since there is a fixed number of excavators and loaders. As the number of trucks is increased, more work is completed faster, but at some point, the excavators and loaders will reach full capacity and additional trucks

will start to affect less and less the duration, until the duration reaches its optimum state.

Now that the models' results have been exposed and studied, the study's main goal can be addressed which consists of evaluating and comparing the two simulation modeling approaches. Given that both models gave the same results and given that these results were reasonable, it can be safely said that both modeling approaches could be used for these types of operations. However, it is important to highlight the advantages of one type over another.

First of all, the first disadvantage found in the DES model is that two select output elements had to be added to the model to improve the model performance. In fact, in the case of earthmoving operations, having such a large number of entities caused the model runs to be slow which led to adding elements that are not related to the model logic. This problem was not faced in the AB model as the movement of vehicles was not determined by entities.

The second disadvantage of DES for earthwork is that for viewers who are not familiar with modeling concepts, understanding the model logic can be difficult. In fact, DES models show entities as moving through a process. In this case, the entities are quantities of soil which are actually static. The way the model is built could be confusing to some. In ABM, understanding the model logic is quite easier as the state-charts do not require simulation modeling knowledge to be understood. In fact, ABM can be quite simpler to understand compared to DES. Although simpler to understand, it is often not easier to create. In fact, ABM models are harder to create because unlike DES, there are no existing and built-in blocks that can be used. The presence of elements such as "service", "source", "sink", and others makes it easier to create a DES model in contrast to ABM which requires additional effort from the user who has to define all types of relationships between the agents present in the model. Although this aspect makes DES easier, it can also be seen as an advantage to ABM. Indeed, the absence of existing elements to be used in ABM provides more flexibility to the modelers to model any scenario in any way they like.

An additional advantage in ABM that was deducted from the model of earthwork operations is the representation of the truck resource. The fact that the truck may be empty or full forced the creation of dummy resources called Empty and Full to discern between an empty and a full truck for the DES model. Since the concept of resources does not exist in ABM, the truck behavior was way better represented through the use of a state-chart as shown in Figure 5.

Based on the aforementioned results and evaluation, the main point to highlight is that ABM can be used for modeling construction operations, namely earthwork

within the same efficiency as DES. This is concluded based on the fact that both yielded the same results. Choosing one of the two methods depends mainly on the modeler's preference, the targeted viewers and the scenario being modeled. Sometimes a simple problem can be built more easily in DES than in ABM, while in the case of a complex one where the building blocks of DES are not enough, it could be more beneficial to build it in ABM to highlight certain parts of the scenario. In our case study, for example, having road segments as agents increased the importance of these parts of the model which wasn't reflected as clearly in DES.

Furthermore, the choice is not always limited to either DES or ABM. In fact, in some cases, the modeler could opt to create a multi-method simulation model to benefit from the advantages of both. A preliminary analysis suggests a potential solution to improve the models created in this paper. The solution is to model road segments and trucks as agents since these two elements were the ones that mainly highlighted the advantages of ABM, while modeling the loaders, excavators and their activities as regular DES processes. AnyLogic software provides the option of integrating different types of simulation modeling including System Dynamics as well. The multi-method model will be fully developed and tested in future works.

4 Summary and Conclusions

This study focused on creating two simulation models for earthwork operations which is one of the most common construction operations. The models were of type DES and ABM respectively. These two models were then tested on a case study in Marjeyoun, Lebanon. The results highlighted the efficiency of both modeling types as both yielded the same results. However, several advantages and disadvantages were highlighted for each type. These can be used by the readers as a guide when selecting the preferred simulation modeling type for a certain scenario. Lastly, a multi-method model was proposed based on the highlighted advantages and disadvantages of each type.

Future works will include a fully developed and detailed multi-method earthwork model. The results and benefits of such a model will be presented, evaluated and compared to similar approaches discussed in the current study. Additionally, further case studies will be done to validate and ensure the credibility of findings.

Acknowledgements

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