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ORIGINAL ARTICLE

Analysis of earth-moving systems using discrete-event simulation

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Abstract Discrete-event simulation has been widely used technique in analyzing construction operations for the past three decades due to its great effect on optimizing cost and productivity. In this paper we will present Arena as a tool for simulating earthwork operations, the advantage of Arena is its easiness and flexibility in simulating most kinds of models in different areas of construction. A case study will be presented, a model will be built and results obtained to reveal the mentioned objectives.

1. Introduction and background

Earthwork operations are one of the most important construction operations needed to be analyzed. Earthwork operations are performed in a highly uncertain environment. These operations include excavation, transportation and placement or disposal of materials. They typically include repetitive work cycles, expensive fleets and large volumes of work. Whereas the planning of these projects can be improved significantly using discrete-event simulation, most projects are still planned using traditional tools. The probable nature of earthwork operations makes it difficult to plan. On site, there will be many decisions that will be taken according to evolving status. A truck, for instance, will be routed to an alternative loading area if the loading unit is under maintenance or trucks are waiting in queue. Each strategy taken in designing the operation will have a direct impact on productivity and cost Han [1], Panas and Pantouvakis [2]. So the importance of using simulation as a tool for accurate planning and estimation of earthwork operations is revealed. Efforts in using simulation in construction industry started with introducing CYCLONE. Martinez et al. [3–5] extended these implementations to object-oriented simulation environments (COOPS, CIPROS, and STROBOSCOPE, respectively). STROBOSCOPE covered limitations found in its predecessors Martinez [4]. For example, Earthmover was introduced by Martinez [5]. It is composed of integrating STROBOSCOPE with Visio, VBA (visual basic for applications) and Excel. A model was introduced by Moselhi and Marzouk [6,7]. Despite these efforts, construction simulation remains at the academic level due to the complexity of simulation methodologies and complexity of the construction process itself AbouRizk and Hajjar [8]. This survey helps fill the gap by introducing a flexible tool for simulating construction operations.

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2. Simulation fundamentals

In order to have a clear understanding of simulation and simulation tools used academically or commercially and using the appropriate tool for a particular problem, a summary of some definitions will be presented. *Simulation* is the imitation of the operation of the real-world process or system over time. The behavior of the system as it evolves over time is studied by developing a simulation model. Simulation models can be classified as either *mathematical* or *physical*. A mathematical model uses symbolic notations and mathematical equations to represent a system – e.g. mathematical models are queuing theory, linear programming and Monte Carlo simulation.

Simulation using a computer language is a particular type of mathematical modeling where a special-purpose computer language is used to model a dynamic system. Physical simulation is the modeling of physical aspects of a system – e.g. a simulator for modeling robotic earth-moving tasks. A static simulation model represents a system at a particular point in time. D*ynamic* models represent systems as they change over time. D*eterministic* model is a model which contains no random variables. S*tochastic* model is a model which contains one or more random variables as input. D*iscrete* model is a model where the state variables change only at a discrete set of points in time and a *continuous* model is a model where state variables change continuously over time. Fig. 1 depicts these classifications.

Now it is clear the advantage of Arena is simulating most kinds of models. It is capable of modeling deterministic, stochastic, discrete and continuous systems in different areas of construction (not only earthwork operations as in the case of special-purpose simulators).

Banks [9] gave several rules for determining when simulation is not appropriate. Simulation should not be used in the following cases:

1. When the problem can be solved either by common sense or analytically.
2. If it is easier to use direct experiment.
3. If costs exceed savings.
4. If resources or time is not available.
5. If data are not available.
6. If the personnel needed to validate and verify the model is not available.
7. If the system behavior is too complex or difficult to be defined.

3. Using Arena

The advantages of Arena from other simulation tools (ex. STROBOSCOPE) Martinez [10] are the easy of data entry and flowcharting methodology for modeling. While others are code-based and require programming skills which need high certain level of training. Arena input interface is shown in Fig. 2. Arena contains three important built-in applications, Input Analyzer, Process Analyzer and Output Analyzer. Input Analyzer is used to test for the input data to fit to the appropriate probability distribution. Process Analyzer is used as a what-if analyzer for different sceneries. Output analyzer is used to analyze output data. Animation is the only tool to have a clear understanding of the system (as in a traffic problem, illustrated in the following case study).

4. Case study

This case study is based upon the example presented by Martinez [5]. He developed Earthmover – i.e. a special-purpose simulator for earthwork operations. The example involves hauling 1,200,000 m^3 of material uphill. The material must be moved in at most 75 working days with up to two eight- hours shift per day. This means that production should be at least 1000 m^3/day. The contractor has two excavators for use in this operation: a Hitachi EX 1100 and an Ekerman EC450. Both excavators must be used because the type of material and load area configuration limit the production of the larger excavator (the EX1100) to 767 m^3/h (6.5 m^3 per 0.43 min pass) and the production of the smaller excavator (EC450) to 515 m^3/h (2.75 m^3 per 0.32 min pass). Both excavators are positioned in two separate loading areas. Fig. 3 shows Earthmover interface with main layout. The big curve segment allows traffic in only one direction. This creates a logistic problem that significantly affects the operation and needs to be investigated. Table 1 shows details of haul segments. A fleet of Volvo A30C6 trucks will be used. The number of trucks is to be determined.

4.1. Operating strategy

This problem will require different operating strategies related to the establishment of traffic direction on the big curve and to the routing of empty trucks toward the two loading areas. The first strategy needed to be tested (simulated) is the direction of traffic in the narrow segment (big curve). This strategy

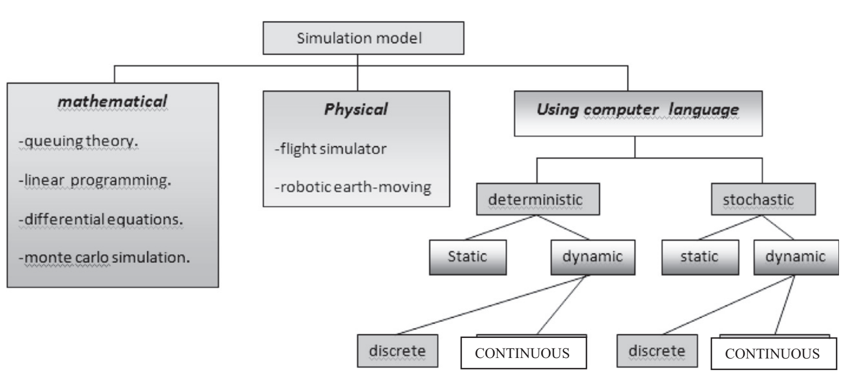

Figure 1 Simulation model classification.

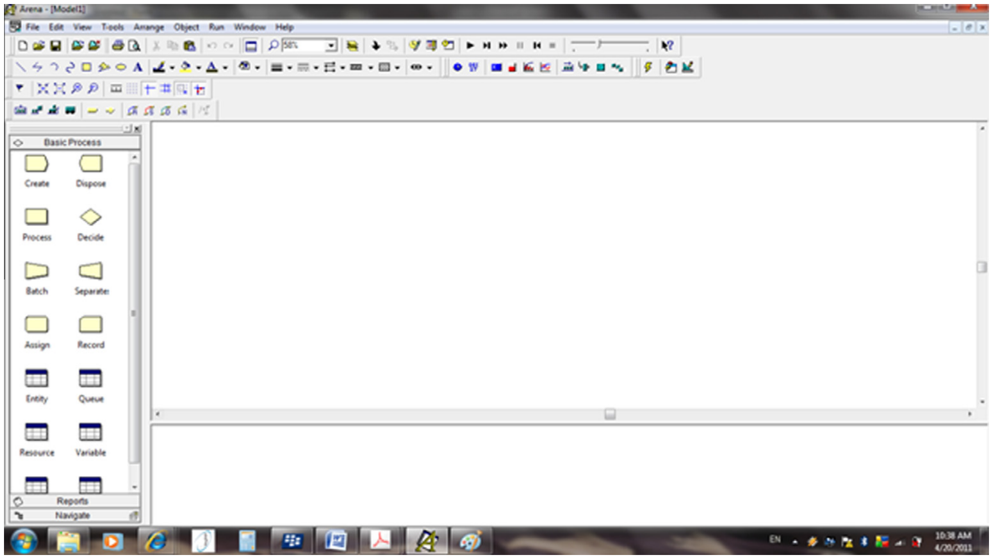

Figure 2 Arena main interface.

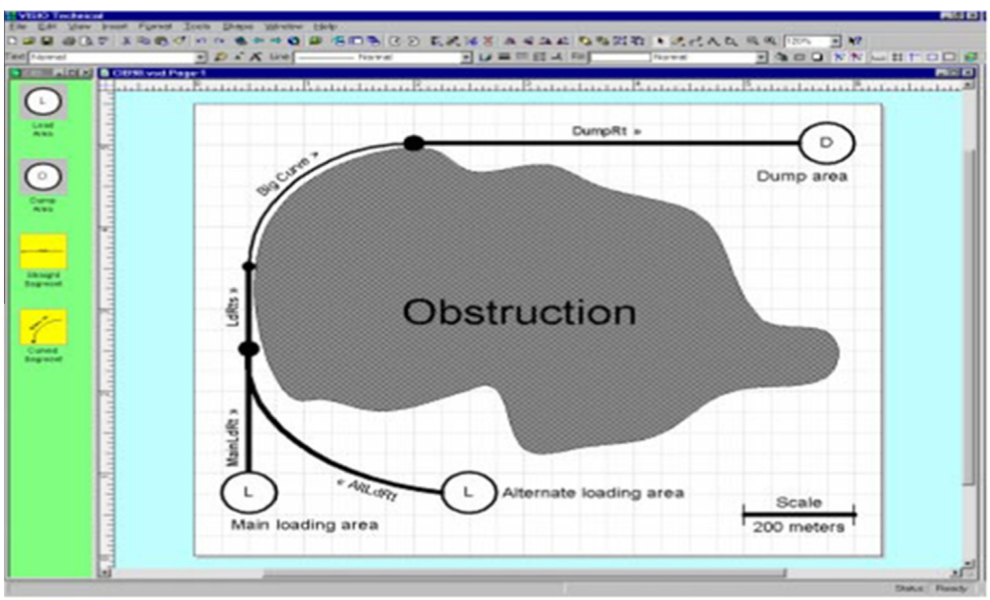

Figure 3 Earthmover interface with main layout.

Table 1 Details of haul segments.

Segment	Length (m)	Curvature Radius (m)	Grade (%)	Rolling resistance	Speed (km/h)	Description
Main LdRt	300	∞	4	4	20.39	Segment is exclusive to main loading area
Alt. LdRT	550	350	7	5	13.59	Segment is exclusive to alt. loading area
LdRts	200	∞	2.5	3	29.65	Shared segment connects both load area to begin curve
Big curve	470	300	3	5	20.39	Shared curve that accommodates traffic in single simultaneous
Dum pRt	700	∞	1.5	3	36.24	Shared segment that connects big curve to dump area.

happens when the segment is empty and the direction of travel is established by the first truck to arrive at the segment. The direction is maintained as long as trucks keep arriving at the segment in that same direction. When the segment is empty, the direction of travel is reversed if trucks were waiting to enter the segment from the other end otherwise it is established by the first truck to arrive at the segment.

Operating strategy of routing of empty trucks toward the two loading areas is assigning a fixed probability (70%) to go to the main loading area and (30%) to the alternative area.

**Speed is derived from this equation $\frac{273.75 * HP}{GVW * TR}$

5. Building the model (for the first operating strategy)

Steps for building a model are Chung [11] as follows:

1. Problem formulation: includes problem definition and establishing the project objectives.
2. Project planning: includes scheduling tasks of the simulation project and assigning roles and responsibilities.
3. System definition: identification of the system components to be modeled, input data, system processes and output measures of performance.
4. Input data collection and analysis: collection of original data, use of existing data and statistical analysis.
5. Model translation: selecting the appropriate simulation software and building the model.
6. Verification, validation: Verification insures that the model operates as intended and Validation determines whether or not the model represents reality.
7. Experimental design: determines which model alternatives will be beneficial to investigate.
8. Analysis: statistical comparisons between alternatives.
9. Presenting conclusion and results: reporting the simulation results.

These are typical steps for building a model, following these steps will vary according to the type and complexity of the simulation project. For instance, for a project where input data already exist and the information about the system is available, step 2 might not be fully done. Now we will follow the required steps for our case:

5.1. Problem formulation

The problem is clearly defined by the given information and the objective of the study was "to find the appropriate number of trucks with an operating strategy to haul 1,200,000 m^3 of material in 75 working days with average production of 1000 m^3/h and maximum excavators utilization according to the mentioned conditions in the problem definition".

5.2. System definition

All system components will be defined as follows:

- Entities will resemble the Volvo A30C6 trucks. The first number of trucks to be tested will be 11 trucks.
- Attributes include trucks' heaped capacity (7.5 m^3) and trucks speeds (Table 1).
- Variables are classified into process variables and global variables. Process variables are loading time in main and alternative loading areas (1.15 min, 2 min). Global variables are variables relative to the system. This will include a number of trucks, a number of working days and overall production – i.e. production per hour, main excavator utilization, alternative excavator utilization, average time to enter curve loaded, average time to enter curve empty, average waiting time at main loading area and average time at alternative loading area.
- *Resources:* include main excavator and alternative excavator.

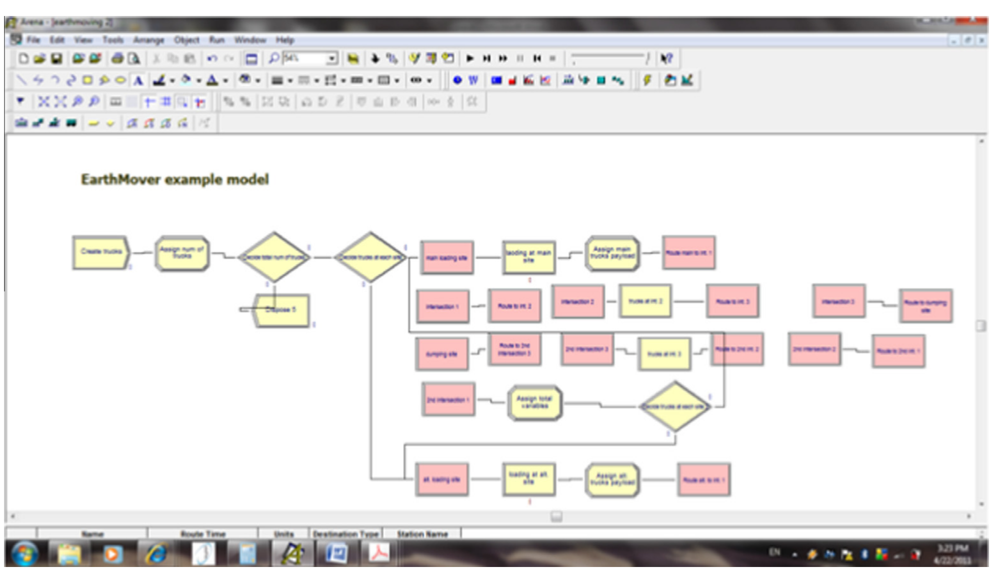

Figure 4 The model built using Arena modules.

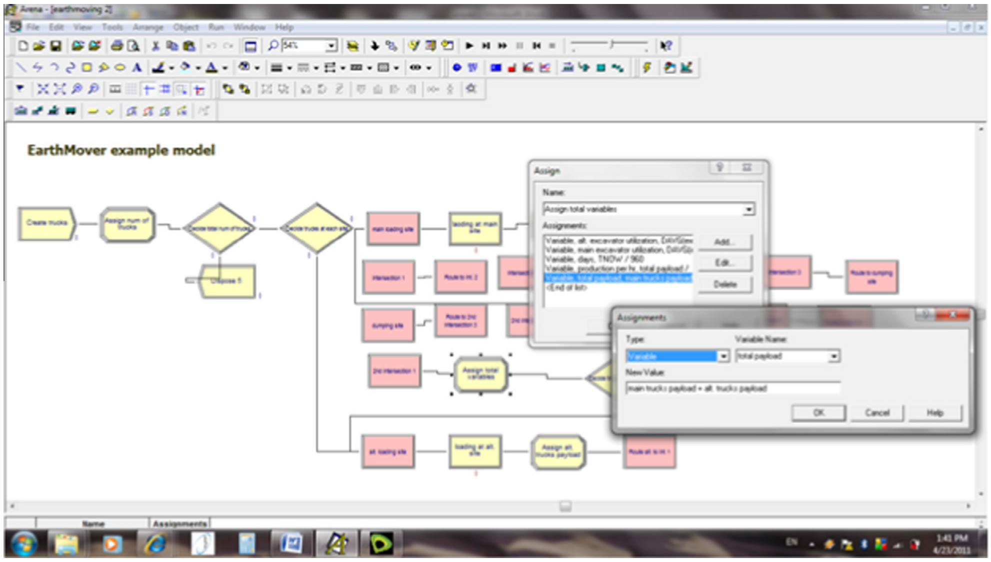

Figure 5 Defining variables.

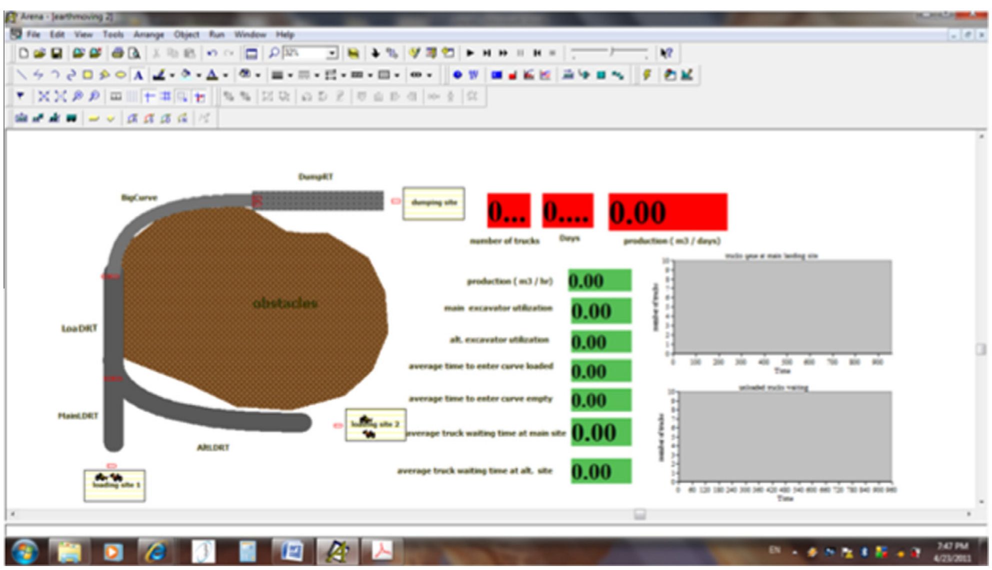

Figure 6 Interface of animation, variables and charts.

- *Queues:* include queues at main and alternative loading area, entrance of curve and entrance of curve from the other end.
- *Input data:* other data required to define the system were determined as inter arrival times and conditions for the operating strategy

5.3. Model translation

A discrete-event simulation software with animation option is the only tool able to solve this problem where operating strategies and traffic problems are the main issues. The model was built by using Arena modules to enter the input data, constructing the logical sequence of the operation according to the first operating strategy and defining variables. Finally, the layout was displayed and the operation animated. Figs. 4–6 show snapshots of the steps taken to build the model.

5.4. Model verification

Animation is the most effective tool for performing basic verification Pegden et al. [12]. By running the model and visualizing the behavior of the system and results of variables or plots, errors can be detected. The model is run in slow motion. The flow of entities (trucks) from the two loading areas heading toward dump site through the one direction segment (big curve) and completing its cycle is observed along

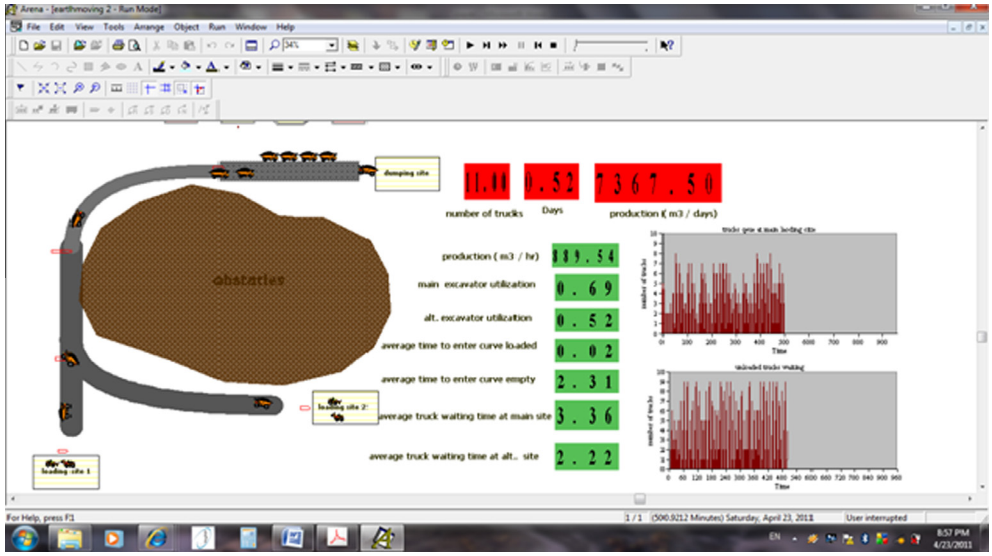

Figure 7 Snapshot during simulation run.

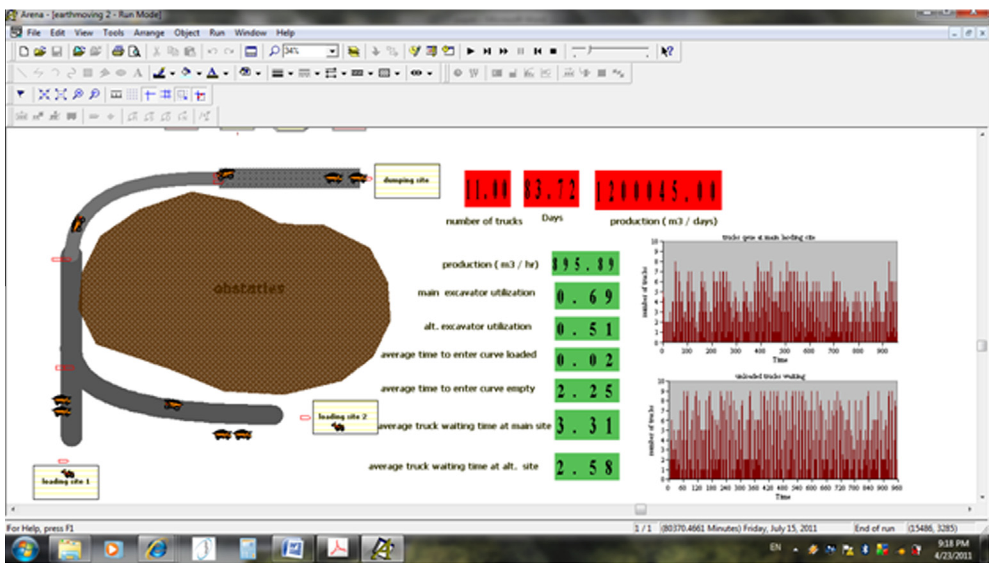

Figure 8 Snapshot of final results.

with observing results of variables and plots displayed to insure that the conditions of the first operating strategy are implemented as intended. Fig. 7 depicts this.

5.5. Experimental design and analysis

The model is run for one replication (as all input data are deterministic) and output results are observed to assess the first operating strategy. Fig. 8 and Table 2 show the final results for the simulation run of the first operating strategy.

These output results show inefficiencies in the operation for the following reasons:

Table 2 Final results for first operating strategy.

Variable	Final result
Number of trucks	11
Total working days	83.72
Daily production (m^3/h)	895.89
Main excavator utilization	69%
Alt. excavator utilization	51%
Average time to enter curve loaded	0.02 min
Average time to enter curve empty	2.25 min
Average waiting time at main site	3.31 min
Average waiting time at alt. site	2.58 min

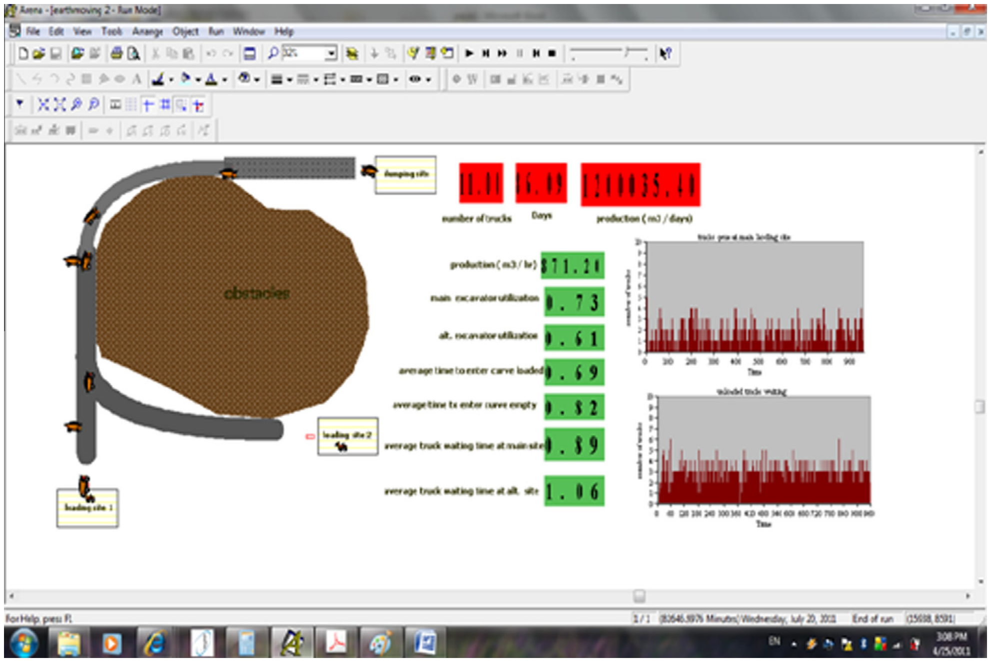

Figure 9 Simulation results of improved strategy.

Table 3 Results of improved strategy.

Variable	Final result
Number of trucks	11
Total working days	86.09
Daily production (m^3/h)	871.2
Main excavator utilization	73%
Alt. excavator utilization	61%
Average time to enter curve loaded	0.69 min
Average time to enter curve empty	0.82 min
Average waiting time at main site	0.89 min
Average waiting time at alt. site	1.06 min

– Utilization of both excavators is low.
– Waiting times for trucks entering curve empty and waiting for excavators at both sites are high.
– Project time and production requirements are not met.

Animation and graphical charts clarified a traffic problem. They show how trucks bunch up before entering the curve empty and then arrive almost together at the loading area. Due to the slow speed, long separation of the loaded trucks enters the curve when another loaded truck has almost passed it completely. This holds the empty trucks for long periods of time waiting to enter the curve and due to the fast speed they

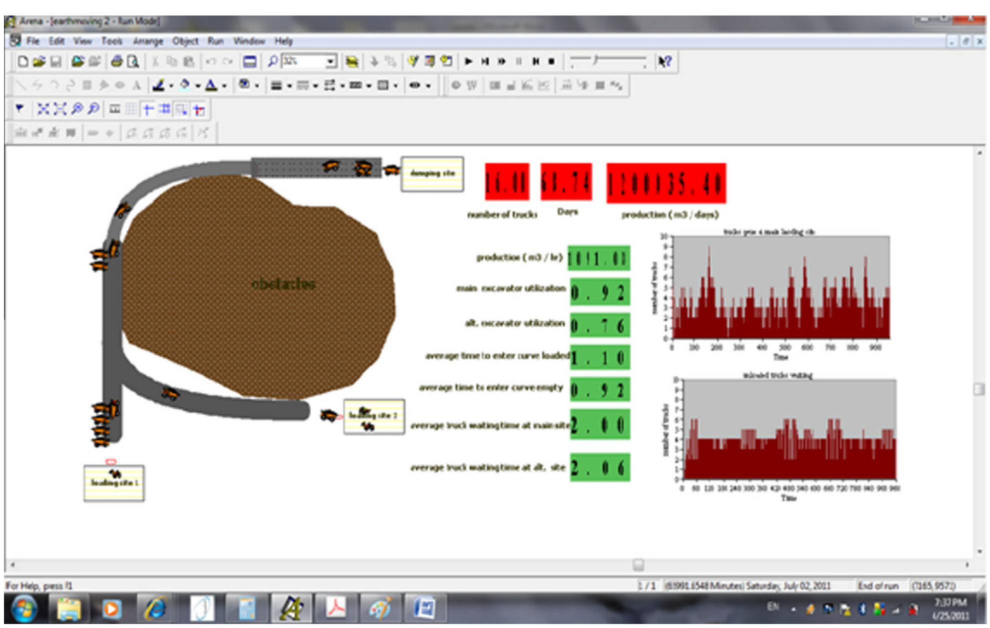

Figure 10 Final simulation results.

Table 4 Final results.

Variable	Final result
Number of trucks	16
Total working days	68.74
Daily production (m^3/h)	1091.03
Main excavator utilization	92%
Alt. excavator utilization	75%
Average time to enter curve loaded	1.1 min
Average time to enter curve empty	0.92 min
Average waiting time at main site	2.00 min
Average waiting time at alt. site	2.06 min

bunch up. To improve inefficiencies found in the first simulation trial, another operating strategy will be established to overcome the bunching problem. This strategy is developed to limit the entry of the loaded trucks to the big curve. A loaded truck is not allowed to enter the curve if the truck ahead of it has traveled 80 m or more and there are empty trucks waiting for the big curve to be cleared at the opposite end. The model was changed to achieve the conditions of the improved strategy. The improved model was run and results obtained as shown in Fig. 9 and Table 3.

It is clear from the results that the performance has improved – i.e. excavators utilization increased, waiting times decreased and the number of trucks waiting at main loading area and waiting to enter the curve empty has decreased (see charts displayed). Despite this, production requirements were not met (at most 75 working days with 1000 m^3/h). After several trials it was found that the optimum number of trucks to achieve these requirements is 16. Fig. 10 and Table 4 clarifies this result.

6. Conclusion

This point of view represents Arena as an alternative tool for simulating construction operations, the effectiveness and capabilities of this tool are demonstrated by introducing a case-study and following typical steps for building a simulation model. Advantages of using Arena are summarized in the following points:

- The ability to model all kinds of problems (deterministic, stochastic, discrete and continuous) in most applications of construction.
- Ease and flexibility in the methodologies of building a simulation model.
- Availability and ease to learn.
- An effective tool to be used academically or commercially.

Disadvantages of Arena:

- The academic version of Arena is limited (a max of 150 entity), so there will be a difficulty in building larger or more complex systems.
- The commercial version is expensive.

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