EARTHMOVER - SIMULATION TOOL FOR EARTHWORK PLANNING

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ABSTRACT

This paper presents EarthMover, a discrete-event special-purpose simulation modeling tool for earthwork planning geared towards practitioners. The paper explores the capabilities of the system by modeling an earth moving operation of moderate complexity. The operation is initially modeled with default parameters and is successively improved based on insights obtained from the static and dynamic outputs of the previous model. The paper also describes the tools and techniques that were used to develop the simulator.

1 INTRODUCTION

Earthwork projects are performed in an environment fraught with uncertainty and using expensive machines that interact in complex ways. While the planning of these projects can be improved significantly using discrete-event simulation, most projects are still planned using traditional tools. Recent advances in general-purpose simulation tools for construction operations modelling, such as STROBOSCOPE (Martinez 1996), enable accurate and detailed modelling of any complex operation. These tools, however, demand a level of training that is beyond that which can be found in most current practitioners. Special-purpose simulators bring the benefits of discrete-event simulation to users with little or no training by providing an environment that is very close to the problem and geared towards a narrow domain.

This paper presents EarthMover, a special-purpose simulation-modelling tool for planning and estimating earth-moving operations. The paper explores the use of EarthMover as a state-of-the-art simulation-modelling tool that allows construction practitioners to model complex earthwork operations in detail. EarthMover supports model definition via an interactive graphical interface where users drag and drop elements such as road segments, bridges, and loading and hauling units. In addition, EarthMover produces static and dynamic output. The static output includes numerous graphs and tables that describe the performance of the system in detail. The dynamic output includes an animation of the simulated system where the loading and hauling units can be seen moving about the site as they perform construction. The animation serves as a verification, validation, presentation, and credibility tool.

The paper also presents the tools and techniques that were used to build EarthMover. These tools and techniques can be readily used to build other special-purpose simulators for building construction as well as for other types of heavy construction. The tools include STROBOSCOPE as a simulation engine, Visio for the graphical and interactive model definition, Excel for tabular and graphical output, and Proof Animation for dynamic output. The techniques include Visual Basic programming and OLE automation.

This paper is a revised version of a paper presented to a limited audience at the 1998 CIB W78 Workshop held in Stockholm, Sweden (Martinez 1998).

2 EARTHWORK

Earthwork operations involve the excavation, transportation and placement or disposal of materials. They typically involve repetitive work cycles, expensive fleets and large volumes of work. Consequently, even small improvements in planning result in substantial cost and time savings. It is for these reasons that earthwork operations improvement has been the focus of so many studies.

The work is performed outdoors under conditions that are highly variable and that affect the performance of the different pieces of equipment. Factors that affect performance include weather (i.e., trucks cannot travel as fast on wet, muddy haul roads), haul road maintenance (i.e., a well-maintained road reduces rolling resistance), operator experience, ground conditions, load and dump area layouts, and the material being excavated.

Earthwork operations are actively managed with many decisions made dynamically on site in reaction to the evolving status. A truck, for example, may be routed to an alternate load area if the loading unit at the main area is under maintenance or if several other trucks are queuing

for it. Sometimes the strategies that guide these dynamic decisions are quite complex but necessary. They can also significantly impact the performance of the operation.

The probabilistic nature of the work and the dynamics of earthwork operations make them difficult to plan. They are typically planned using simplified back-of-the-envelope calculations, but mainly relying on the experience and insights of the planner. Discrete-event simulation is the only earthwork analysis method that can explicitly incorporate the detailed but significant aspects (e.g., equipment characteristics, haul road conditions, load and dump area configuration, and dynamic context-based decisions) of an operation. The preparation of a detailed and precise simulation model, however, typically requires the use of a general-purpose simulation programming language. These advanced tools require extensive training that is not generally available in the personnel responsible for planning.

3 EARTHMOVER

The benefits of detailed and advanced discrete-event simulation can be brought within the reach of domain experts with the use of special-purpose tools. These tools target a narrow domain such as pipe-laying, earth-moving, or concrete-pouring. The reduced domain allows them to address complex domain-specific problems at the expense of generality. The capability to handle complex cases, however, is greatly dependent on the specific tool and is not an attribute of all special-purpose simulators. In particular, a simulator must offer some programmability and end-user extensibility to enable the modelling of specific problems not pre-solved by the tool designer (Law and Kelton 1991).

The tool presented here, EarthMover, is a programmable and extensible special-purpose simulator for earthwork operations modelling currently under development at Virginia Tech. EarthMover has evolved from what originally was the final project in a graduate-level simulation course (Martinez 1997). Due to its modular design, the simulator can be used "as is" to model a wide variety of earthwork operations.

3.1 EarthMover: Current Status

In its current stage of implementation, EarthMover incorporates very detailed modelling of the transport portion of an operation, including facilities to define dynamic truck routing strategies and one lane (but bi-directional) haul road segments. The loading portion of an operation is currently limited to stockpiled material, or to material that can be excavated by the loading units. This assumes that the preparation of material for loading does not constrain the system. The dumping portion of an operation is currently limited to spreading of material using

a spreading unit such as a bulldozer. This assumes that the compaction of the spread material does not constrain the system either.

The input to the system consists of:

1) A description of horizontal haul road geometry and location of load and dump areas via interactive drawing tools - users draw a plan view of the haul system. EarthMover determines segment lengths, horizontal curvatures, and road forks (points at which trucks have the opportunity to select from among several possible routes) from this drawing.

2) Form-based detailing of the characteristics of individual segments and areas - users double-click a segment to bring up an input form. The details for segments include the rolling resistance, ground class, width, grade, and coefficient of traction (for standard rubber tires) of each segment. The details for one-lane bi-directional segments include the policies on when to switch direction and other specific values that depend on the specific policy that is chosen. The details on segments that follow a fork include formulas that describe the relative likelihood that a truck will take that particular branch. Details on loading areas include the total amount of material available for excavation from the area as well as the characteristics of the material.

3) Selection of the equipment fleet used in the operation from a user-updateable ASCII database. The database includes different models of hauling, loading, and spreading units. Hauling unit characteristics include empty and maximum weight, rated capacity, engine power, maximum speed, loaded and empty weight percentage on driving wheels, overall length, mean time between break-ups, repair time distribution, and move-in and hourly cost.

4) General data that applies to the entire job such as random number seed values, maximum simulation time, overhead cost, and output options.

Based on the input described above, EarthMover simulates the model and produces static output in the form of tables and charts, and dynamic output in the form of animation. The most important are the total cost and time of the operation. Tables and charts describe the distribution of waiting times at different parts of the haul system, the utilisation of the load and spread units, and the distribution of travel times at each segment.

EarthMover is implemented as a system that uses the strengths of four separate applications. Visio (Visio Corporation 1997) is used as the graphical input front end. The support for Visual Basic for Applications (VBA) in

Visio is used to present the input forms that capture the non-graphical component of the input. STROBOSCOPE (Martinez 1996) is used as the simulation engine – it performs the actual number crunching necessary to model the operation, to create the trace file needed for animation, and the numbers behind the output tables and charts. Excel (Microsoft Corporation 1997) is used as the output mechanism for tabular data and charts. Proof Animation (Henricksen 1997) is used for dynamic output – based on geometry extracted from Visio and the trace file generated by STROBOSCOPE, it can animate the modelled operation in detail. STROBOSCOPE and Excel are controlled via OLE Automation from within a main program written using VBA within Visio. Proof Animation is launched using system commands by the VBA code in Visio.

4 EXAMPLE

The EarthMover system is best illustrated with an example, which in this case 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-hour shifts per day. This means that production should be at least 1000 m^3/hr. The contractor has two excavators for use in this operation: a Hitachi EX1100 and an Åkerman 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/hr (6.5 m^3 per 0.43 minute pass) and the production of the smaller excavator (the EC450) to 515 m^3/hr (2.75 m^3 per 0.32 minute pass). Both excavators must be used, and in this case positioned in two separate loading areas. The distances from these loading areas to the fill are 1,670 meters (from the main area) and 1920 meters (from the alternate area). The haul routes share 1,370 meters, including a long and narrow curve 470 meters in length. The long and narrow portion is not wide enough to allow simultaneous traffic in both directions. This creates a logistics problem that significantly impacts the operation

and which must be investigated. Table 1 shows the details of the haul segments. The contractor will use a fleet of Volvo A30C 6-wheel-drive articulated trucks. The number of trucks to use is to be determined.

4.1 Basic Input

Figure 1 shows the main EarthMover screen. The right side shows a plan view of the haul system. The left side shows a stencil containing objects that can be dragged to the plan view to create the haul system. The segments that compose the haul system are named, and the direction of travel when loaded is indicated with the "»" character. EarthMover ignores drawing objects that are not part of the model. Visio's standard drawing tools can thus be used to annotate models or to illustrate certain aspects of the operation such as the big obstruction shown. EarthMover is able to extract segment distances and radii of curvature from the drawing itself. The rolling resistance, grade, and unique segment name are specified by the user with input forms that appear when a segment is created or double-clicked.

The equipment to be used in the operation is defined as part of the data that detail the loading and dumping areas. For the initial run, for example, the main loading area was assigned the EX1100 with eight A30C's initially queued up to load; the alternate loading area was assigned the EC450 with three A30C's queued up to load. Although trucks are assigned to start in a particular location (loading areas in this case), they are not restricted to load or dump at a specific location.

4.2 Operating strategy

There are two aspects of this operation that require operating strategies as input. These relate to the establishment of traffic direction on the big curve and to the routing of empty trucks towards the two loading areas.

Table 1: Haul Road Segments

| Segment	Length (m)	Curvature Radius (m)	Grade (%)	Rolling Resistance (%)	Description
MainLdRt	300	∞	4	4	Segment is exclusive to the main loading area
AltLdRt	550	350	7	5	Segment is exclusive to the alternate loading area
LdRts	200	∞	2.5	3	Shared segment that connects both load areas to the long narrow curve
BigCurve	470	300	3	5	Long and narrow shared curve that accommodates traffic in a single simultaneous direction
DumpRt	700	∞	1.5	3	Shared segment that connects the long narrow curve to the dump area
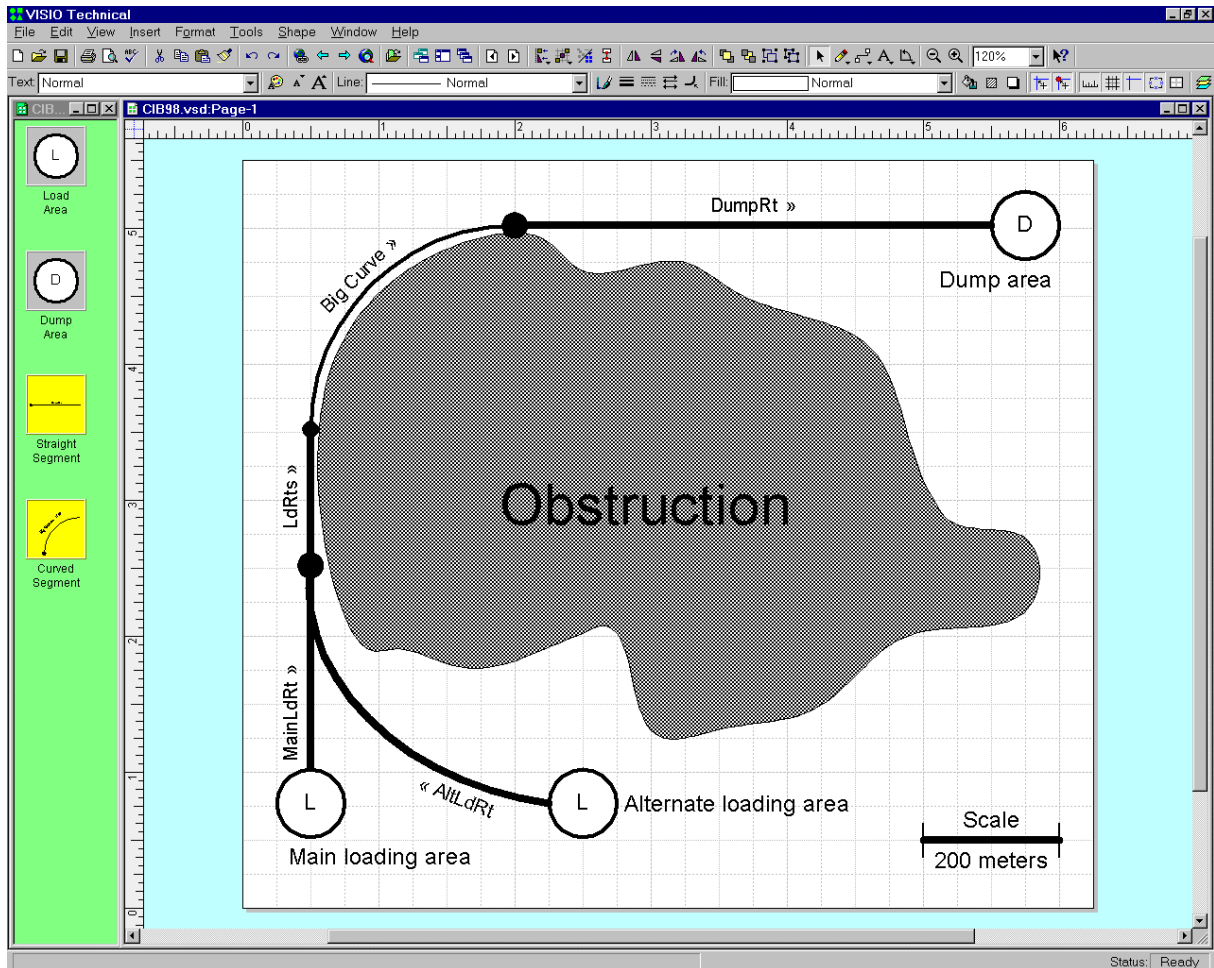
Figure 1: EarthMover Main Interface, Showing Discussed Example

The first strategy to test for establishing the direction of traffic in a narrow segment is the one EarthMover uses by default. This is the simplest and is indicated by selecting that option from a list. When the segment is empty, the direction of travel is established by the first truck to arrive at the segment. This 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.

There are many ways to route the empty trucks to the two loading areas. EarthMover supports the assignment of specific trucks to a specific loading area; the routing of trucks in a fixed repeating pattern such as three to the main area and then one to the alternate area; routing with fixed probabilities of taking a particular direction; and dynamic routing based on the current scenario. The first strategy

tested here assigns a fixed probability of 70% to go to the main area and 30 % to go to the alternate area (these are the probabilities that yield the best results).

4.3 Initial trial results

The basic output for a single run with the first set of strategies looks as follows:

- Number of Trucks: 11

- Total days: 108.37 days

- Production: 692.09 m3/hr

- Main excavator utilisation: 63.28%

- Alternate excavator utilisation: 40.04%

- Average time to enter curve loaded: 0.05 minutes

- Average time to enter curve empty: 2.81 minutes

- Average truck waiting time at main loading area: 3.42 minutes

- Average truck waiting time at alternate loading area: 2.11 minutes

There are some obvious inefficiencies in the operation because the utilisation for both excavators is low while the waiting times for trucks entering the curve empty and waiting for the excavators are high. The project time requirement and production are not met, although the trucks or the excavators, when considered independently, should yield well above 1000 m3/hr.

A better insight into the operation and its problems are obtained by looking at the graphical output. Perhaps the most interesting of the charts are the ones shown on *Figure 2* and *Figure 3*. These charts show the number of trucks waiting to enter the curve empty and waiting for the main excavator as a function of time. The charts produced automatically by EarthMover span the entire operation time. They were edited in Excel to show only the 3rd to 5th hour of the operation.

Notice that both charts look like the skyline of a city with tall but separated skyscrapers. They show how trucks bunch up before entering the curve empty and then arrive almost together at the loading areas. A similar chart for the use of the excavators shows that they are very active for periods of time (serving several trucks that bunched up), followed by periods of inactivity waiting for another bunch of trucks to arrive.

The dynamic output produced by EarthMover provides a much better picture of the truck bunching and additionally reveals strategies that could be used to improve the operation. *Figure 4* shows a snapshot of the animation with seven trucks bunched up waiting to enter the big curve; another empty truck about to join the bunch; one loaded truck heading towards the dump area; one loaded truck in the middle of the big curve; and another loaded truck about to enter the big curve.

The slow speed of the loaded trucks and the fast speed of the empty trucks as they traverse the big curve cannot be seen on the snapshot. Only the animation can convey that information. Due to the slow speed and long separation, loaded trucks often enter the curve when another loaded truck has almost passed it completely. This holds the empty trucks for long periods of time during which they bunch up.

Figure 5 shows a snapshot of the animation four minutes later, when the trucks that had bunched up have arrived almost together to the loading areas. Two trucks are out of view in the snapshot but will soon also arrive to the loading areas.
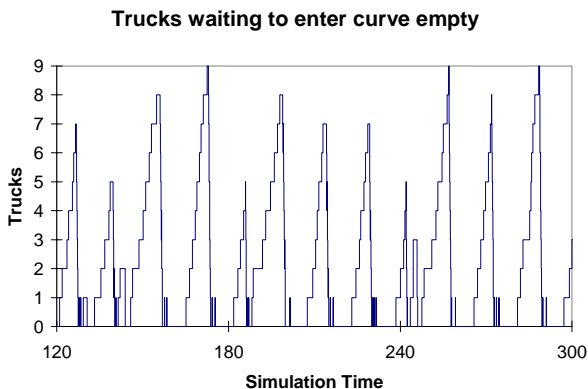

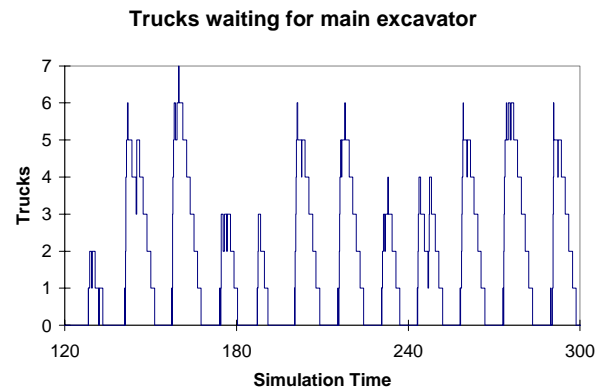Figure 2: Trucks Waiting to Enter Curve Empty for the First Trial Run

Figure 3: Trucks Waiting for the Main Excavator During the First Trial Run
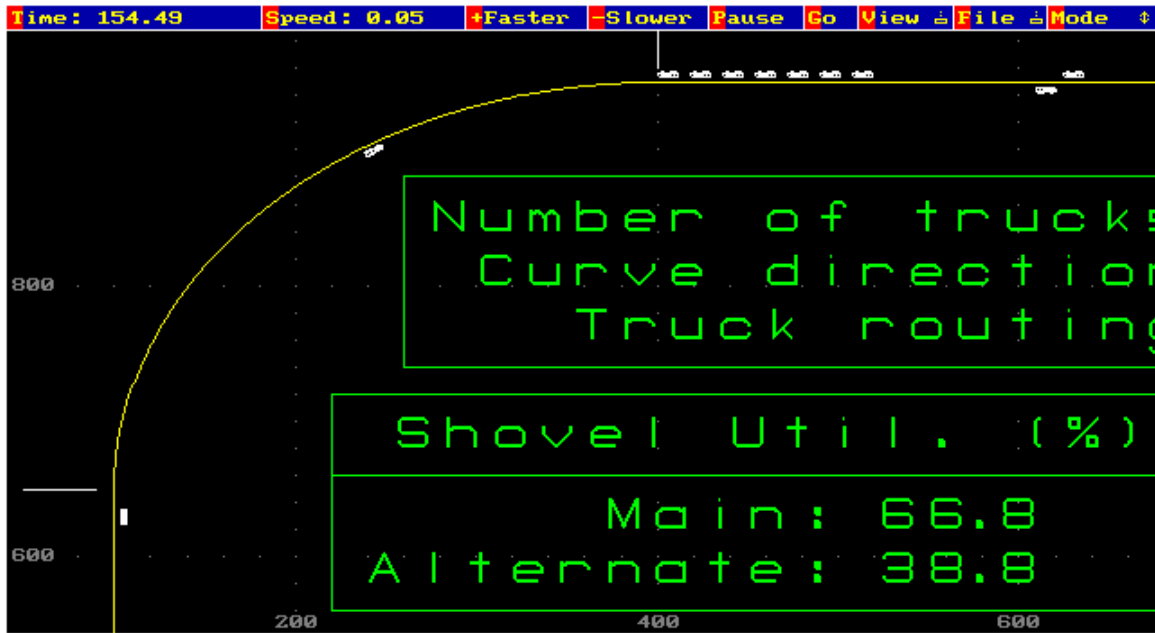
Figure 4: Animation SnapShot Showing Bunched up Trucks Waiting to Enter the Big Curve

4.4 Improvements to Operation Design

Guided by the insights obtained from the static and dynamic output of the initial run, it is possible to establish operating strategies that may significantly improve the operation. In this case, the bunching problem is the most significant. A strategy that may be used to solve it is to limit the entry of loaded trucks to the big curve. A loaded truck is not allowed to enter the big curve if the truck ahead of it has travelled 80 meters or more and there are
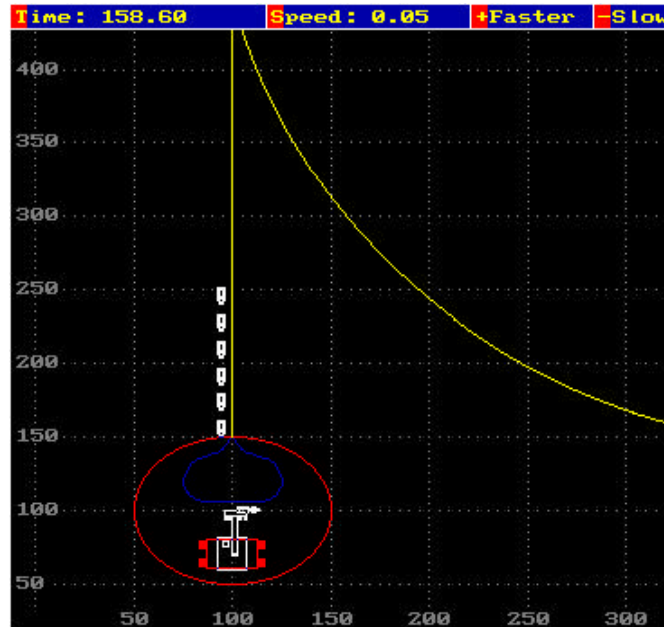

Figure 5: Animation Snapshot Showing Bunched Trucks
Waiting for Excavators

empty trucks waiting for the big curve to be cleared at the opposite end. When implemented, this strategy still leaves a small amount of bunching, but significantly increases the utilisation of the excavators. The basic results from implementing this strategy are as follows:

- Number of Trucks: 11, better direction control on curve

- Total days: 87.65 days

- Production: 855.70 m3/hr

- Main excavator utilisation: 78.12%

- Alternate excavator utilisation: 49.70%

- Average time to enter curve loaded: 0.76 minutes

- Average time to enter curve empty: 1.04 minutes

- Average truck waiting time at main loading area: 1.07 minutes

- Average truck waiting time at alternate loading area: 0.72 minutes

Note the production increase of about 24% due to a simple change in operating procedure. *Figure 6* shows the number of trucks waiting to enter the curve empty as a function of time and illustrates the effect of the strategy on bunching (compare to *Figure 2*). Production is still low and not sufficient to meet job requirements–more trucks need to be used.

Subsequent trials with more trucks indicate that to meet production requirements it is necessary to use 16 trucks, with results as shown below:

- Number of Trucks: 16, improved direction control on curve

- Total days: 71.61 days

- Production: 1047.38 m3/hr

- Main excavator utilisation: 94.40%

- Alternate excavator utilisation: 62.84%

- Average time to enter curve loaded: 1.15 minutes

- Average time to enter curve empty: 1.30 minutes

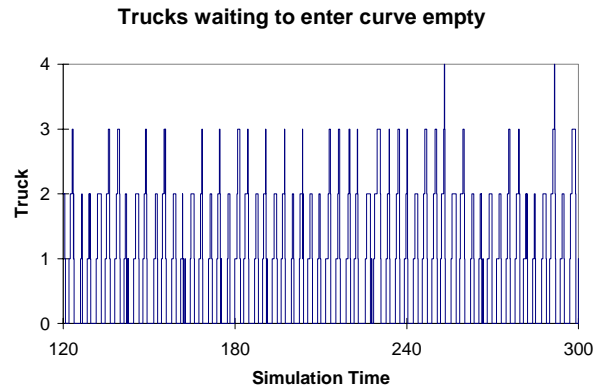**Trucks waiting to enter curve empty**

Figure 6: Trucks Waiting to Enter Curve Empty on Second Trial Run

- Average truck waiting time at main loading area: 3.08 minutes

- Average truck waiting time at alternate loading area: 1.28 minutes

By observing the corresponding animation, however, it was obvious that the strategy for routing trucks to the load areas could be improved. Based on the average times of service and travel, which do not depend on queuing, it is possible to establish a calculated routing rule. The rule is given by the truth of the following condition:

```
MnTrucks>(AltTrucks+1.5)*1.47-0.09
```

In the above condition, *MnTrucks* is the number of trucks waiting or headed towards the main loading area and *AltTrucks* is the number of trucks waiting or headed towards the alternate loading area. The condition is evaluated dynamically just before routing each truck. When the condition is true, a truck is routed to the alternate loading area. Otherwise, it is routed to the main loading area. Although this strategy may be difficult to implement in practice, simpler forms may be applicable. When this strategy was implemented with 16 trucks, production increased to 1083.41 m3/hr. This increase in production prompted testing with fewer trucks. Using fourteen trucks was often good enough to meet time requirements, but sometimes fell short. The long-term production was 999.75 m3/hr. Fifteen trucks consistently yielded production above 1000 m3/hr. The results for a run with 15 trucks are shown below:

- Number of Trucks: 15, better direction control on curve, intelligently routed

- Total days: 71.64 days

- Production: 1046.90 m3/hr

- Main excavator utilisation: 99.99%

- Alternate excavator utilisation: 54.48%

- Average time to enter curve loaded: 1.05 minutes

- Average time to enter curve empty: 1.28 minutes

- Average truck waiting time at main loading area: 2.51 minutes

- Average truck waiting time at alternate loading area: 0.03 minutes

These results point to the potential gains that may be obtained with intelligent dynamic routing. Evidently, the route towards the main shovel is more efficient because it is shorter, not as steep, and because the EX1100 is capable of producing higher output. Consequently, the "smart" routing attempts to keep the main excavator fully utilised. This is evident with the reported utilisation of 99.9% (for the purposes of discussion, we assume that such a high utilisation is feasible and desirable).

Figure 7: STROBOSCOPE network Fragment to Represent a Loading Area

5   DEVELOPING EARTHMOVER

The main EarthMover program is hosted under Visio Version 4.5 or later. The code on the Visio side is divided into two parts. One part is defined by the master shapes that reside in the stencil and the shape-sheet formulas they contain. The other part is defined using Visual Basic for Applications (VBA) from within Visio.

The VBA code brings up forms to edit the properties of the haul system components. The VBA code is also responsible for assembling a STROBOSCOPE simulation model based on the drawing data, and for preparing a Proof Animation Layout file. The VBA code, for example, expands a loading area that uses excavators or front shovels to the fragment of STROBOSCOPE network shown in *Figure 7*. Other haul system components, such as haul segments, are expanded in a similar manner and linked to other expanded components. The assembled network is communicated to STROBOSCOPE using OLE Automation. The STROBOSCOPE code assembled by Visio VBA contains instructions that generate data files for use in preparing output tables and charts. They also contain instructions that generate Proof Animation trace files. The Visio VBA code uses OLE Automation to create tables and charts in Excel based on the data files generated by STROBOSCOPE. The Visio VBA code can also invoke Proof Animation with the layout prepared by itself and the animation files generated by STROBOSCOPE.

6   CONCLUSION

This paper presented a special-purpose programmable simulator for earthwork operations. The capabilities, simple input requirements, and effectiveness of the tool were demonstrated with an example. The paper also described the construction and design of the simulator based on four separate applications: Visio, STROBOSCOPE, Excel and Proof Animation. These tools can also be used to create other special-purpose simulators for use in building construction, other types of heavy construction, and manufacturing.

More information on these development tools can be obtained from the Internet at the following URL's:
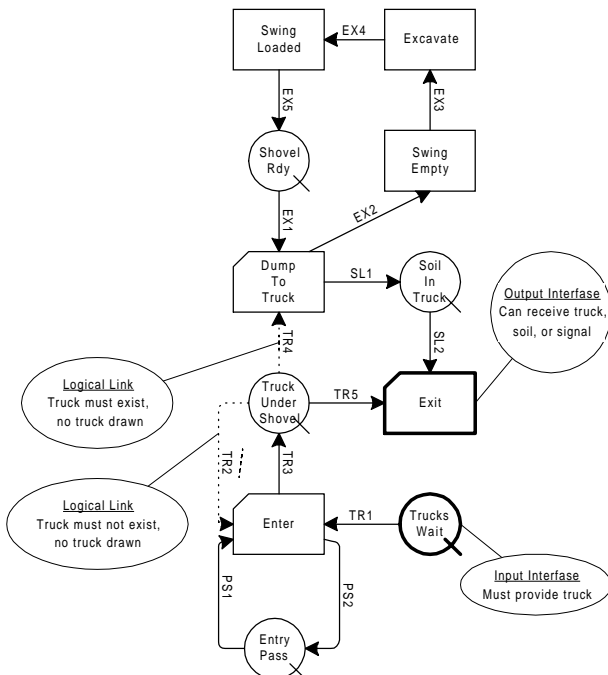
STROBOSCOPE: http://strobos.ce.vt.edu

Visio: http://www.visio.com

Excel: http://www.microsoft.com

Proof Animation: http://www.wolverinesoftware.com

ACKNOWLEDGEMENTS

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