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SIMULATION OF EARTHMOVING FOR A DAM USING ENGINEERING CALCULATIONS

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ABSTRACT

Detailed STROBOSCOPE simulations of earthmoving for the construction of a dam use the engineering calculations typically employed in heavy construction to estimate equipment performance based on the characteristics of the haul and return roads and the mechanical properties of actual models of heavy loaders and trucks. Sensitivity analysis investigates the total cost of truck combinations while considering the traffic effects of one or two bridges needed to cross a river along the haul route. This example can serve as a simulation model template to facilitate the wider acceptance of simulation in heavy construction practice.

1 INTRODUCTION

1.1 Importance of Heavy Construction Equipment

Heavy construction equipment used for civil engineering earthwork, such as excavators, loaders, trucks, scrapers, graders, etc., are of great importance in the planning and performance of construction operations due to their effectiveness and their high ownership and operating costs. The body of research related to construction equipment is so wide that several studies (Edwards and Holt 2009; Naskoudakis and Petroutsatou 2016; Chen et al. 2022) have attempted its classification into related themes such as maintenance, downtime, productivity, optimization, robotics, automation, health and safety, operator competence, machine control, monitoring, innovation, and environment.

In the theme of productivity and optimization, equipment-related decisions can be classified into those made during the planning and estimating stage (before construction begins), and decisions made during actual construction for monitoring, evaluating, and controlling equipment operations. This paper focuses on decisions made during the planning and estimating stage. An example of research on automating decisions about field operations that require the dynamic synthesis of information generated from different parts of the jobsite in real time via IoT infrastructure can be found in (Louis and Dunston 2017).

1.2 Earthmoving Simulation for Construction Planning and Estimating

Earthmoving for major civil engineering heavy construction works, such as dams, levees, or highways, has been a typical application area for construction simulation models to estimate costs and project duration, and to find the optimum spread of equipment for the job before construction begins (Ioannou 1999; Martinez et al. 1994). In these applications, heavy-duty trucks are loaded with material at the borrow area by large excavators or loaders, and then travel to the project site, sometimes over considerable distances, dump at the appropriate locations under the guidance of one or more spotters, and return empty to load again and repeat the cycle. Often, the haul and return travel times are modeled as random variables generated from distributions that are assumed to have already been estimated. Missing from these models are the engineering calculations typically performed by heavy construction contractors based on the length, grade, and rolling resistance of the haul and return roads and the actual mechanical characteristics of the trucks that will haul the material. Given the high costs of heavy construction projects and the industry's conservatism in choosing appropriate analysis and decision support systems, these types of equipment performance calculations are an important prerequisite for the wider acceptance of simulation in practice.

This paper presents a STROBOSCOPE simulation model that illustrates how to model the performance of heavy earthmoving construction equipment by using engineering calculations as is usually performed in practice. Specifically, the example shows how to model the loading and hauling of material for the construction of a dam based on the characteristics of the haul and return roads and the mechanical properties of actual models of loaders and trucks, such as bucket size, engine power, transmission efficiency, retarding power, etc. Engineering calculations are used to determine equipment performance such as the time needed to load a truck, the amount of material loaded in each truck, a truck's speed on each road segment depending on its grade and rolling resistance, and the time to traverse each road section depending on its length. The types of engineering calculations involved are those that are typically performed manually by heavy construction contractors to estimate equipment performance, to determine the spread of equipment to be used on a job, and ultimately to estimate the bid amount to submit (Peurifoy et al. 2018). The difference is that the simulation model presented here incorporates stochastic considerations and the effects of queueing that exceed the capabilities of traditional calculation methods. Also, the presented model can serve as a starting template for estimating performance and cost for other heavy construction projects that use large construction equipment to load and haul material under project-specific transportation conditions.

2 EARTH HAULING FOR A DAM

2.1 Project Overview

The construction of a dam requires hauling 500,000 m^3 of soil from the borrow area to the project site. Two models of heavy wheel loaders, one CAT 950E and two CAT 936E, will be used to load soil into heavy trucks of two types, CAT 773B and CAT 769C. The number of trucks for each truck model that minimize total cost are to be determined. Table 1 shows the properties of the CAT 950E and CAT 936E wheel loaders. Table 2 shows the characteristics of the CAT 773B and the CAT 769C trucks.

The density of the loose soil to be hauled is 1690 kg/m^3. The trucks load with soil at the borrow area, haul the material to the dam embankment, dump, and return empty. Each truck arriving at the borrow area waits in line and is loaded in FIFO order by the next available wheel loader. The total time to load each truck depends on the model characteristics of the loader and the truck and includes the time to maneuver into loading position as shown in Table 1 and Table 2.

Table 1: Loader characteristics.

Model	CAT 950E	CAT 936E
Machines available	1	2
Bucket Size (m^3)	2.4	2
Soil loaded in loader's bucket, S (m^3)	Bucket Size * N[1,0.04]	Bucket Size * N[1,0.05]
Time to load a bucket of soil in truck (min)	$0.43+0.035S$	$0.40+0.05S$
Cost ($/hr)	130	90

Once the truck is in loading position, the loader starts putting buckets of soil into the truck. The amount of soil S (m^3) in each bucket varies around the nominal loader bucket size as shown in Table 1. The time in minutes to load one bucket of soil into a truck has a fixed time component and a variable time component that depend on the type of loader and the actual amount of soil S in the bucket as shown in Table 1.

Trucks are loaded with soil for as long as the amount of empty space in the truck exceeds one half of the loader's bucket size. Thus, the last bucket must bring the material loaded in the truck to at least within half a loader's bucket from the truck's capacity. This means that the total material loaded into each truck varies and may sometimes be a little below and sometimes a little above the truck's nominal capacity.

Table 2: Truck characteristics.

Model	**CAT 773B**	**CAT 769C**
Machines available	To be determined	To be determined
Capacity (m^3)	34.1	23.6
Mass when empty (kg)	39,396	31,178
Flywheel Power (kW)	485	336
Transmission efficiency	0.84	0.82
Retarding power (kW)	526	434
Max. speed (km/hr)	62	75
Actual speed (km/hr)	Calc. speed *N[1,0.02]	Calc. speed *N[1,0.03]
Dumping time (min)	1.12	1
Maneuvering time at loading area (min)	0.72	0.6
Time to cross most economical bridge (min)	2.5	1.5
Cost ($/hr)	300	230

After a truck is loaded, it starts hauling the soil from the borrow area to the dam embankment. The first road segment descends towards a river, where trucks must cross a bridge as described below, and the second segment ascends towards the dam embankment. Table 3 shows the characteristics of the two road segments, from the borrow area to the bridge and from the bridge to the dam embankment.

Table 3: Haul and return road segment characteristics.

Haul and Return Road Segment	Length	Grade	Rolling Resistance
Borrow area to Bridge	2.3 km	-4% (descending)	7%
Bridge to Dam Embankment	1.7 km	6% (ascending)	4%

The speed and time for a truck to traverse each road segment is determined by engineering calculations based on the road data in Table 3, the truck's properties in Table 2, and the truck's total mass when hauling loaded or returning empty (instead of using the rimpull and retarding graphs that are typically provided in equipment performance manuals). Acceleration and deceleration times are short and are ignored.

Upon arrival at the dam embankment, trucks are directed by a single spotter to the appropriate location to dump. Because of this, trucks form a FIFO queue and dump one at time.

2.2 Crossing the River—Temporary Bridge(s)

The bridge currently crossing the river does not have the necessary capacity to support heavy trucks. As a result, at least one temporary bridge would have to be constructed. The most economical bridge alternative can accommodate only one-way traffic, can support only one truck at a time, and trucks must slow down to cross the bridge as shown in Table 2. Sensitivity analysis will investigate if having two such bridges, each dedicated to one direction of traffic, or whether a more expensive alternative of two one-way bridges that can support multiple trucks traveling at higher speeds might provide better economic options.

3 SIMULATION OF EARTHMOVING FOR DAM CONSTRUCTION

The simulation models of earthmoving for dam construction using the above data were developed using the STROBOSCOPE simulation system (Martinez and Ioannou 2023). STROBOSCOPE is a general-purpose discrete-event simulation system based on three-phase activity scanning that is particularly suited for modeling the resource interactions of complex construction processes. At a high level, STROBOSCOPE models can be represented by networks of nodes and links that resemble activity cycle diagrams. The simulation model networks shown in the figures of this paper were developed using STROBOSCOPE's graphical user interface (GUI) which is implemented in Microsoft Visio using a custom dynamic link library. The network representation, the definition of resource objects and their properties, the interactions between resources, as well as the details and complexities of the model are represented in STROBOSCOPE's simulation programming language that provides full access to dynamic variables, the dynamic properties of resources, and the state of the simulation. As an overview, the STROBOSCOPE language allows modeling stochastic resource production, utilization, and consumption; smart resource allocation; compound resources that encapsulate other resources to any level; and dynamic decisions regarding the sequence of activities. The STROBOSCOPE program, its documentation, and several examples are available at (Martinez and Ioannou 2023). The STROBOSCOPE system and language are described in (Martinez 1996). Example applications can be found in (Ioannou and Martinez 1995, 1996a; b; Martinez et al. 1994; Martinez and Ioannou 1994, 1995).

The STROBOSCOPE simulation network for the construction of a dam using one one-way bridge as described above is shown in Figure 1.

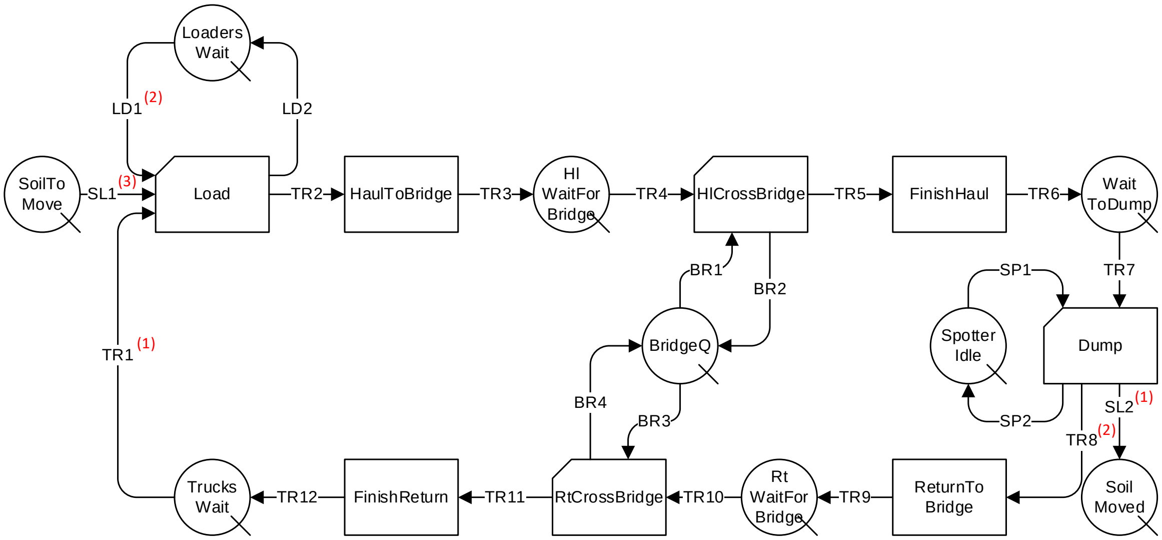

Figure 1: STROBOSCOPE simulation network for dam construction using one one-way bridge.

This network consists of nodes and links. Queues are shown as circles resembling the letter "Q" and each holds idle resources of a certain type such as *Truck*. Combi (conditional) activities are shown as clipped rectangles that require resources in order to start and are preceded by queues. Normal (bound) activities are shown as rectangles and can start whenever a direct predecessor activity finishes. Links connect the nodes and indicate the flow of the various types of resources in the model.

The following sections describe only the main STROBOSCOPE statements that were used to build the simulation models of the earthmoving operations for dam construction. STROBOSCOPE statements such as those that define the nodes and links for the networks shown in the figures are implied and have been omitted for brevity. The complete models are available from the author.

3.1 Generic and Characterized Resources

In this STROBOSCOPE model, the resources *Soil*, *Bridge* and *Spotter* do not need to be associated with specific properties and are modeled as generic resources.

```
GENTYPE      Soil; GENTYPE    Bridge; GENTYPE     Spotter;
```

The loaders and trucks are modeled as characterized resources with as many static and dynamic properties as needed for model completeness. Shown below is the definition of the characterized resource type *Loader* with five properties, which include the loader's bucket size (m^3), the standard deviation of the volume of soil in each bucket over the bucket's nominal size, the fixed component of time to load a bucket with soil (minutes), the variable component of the time to load a bucket per m^3 of soil in the bucket (minutes/m^3), and the hourly cost of the loader ($/hr). The two types of wheel loaders in this project, *S936E* and *S950E*, are defined as subtypes of *Loader* and their numerical properties are those shown in Table 1.

```
CHARTYPE  Loader       BucketSize LoadVariability FixedLdTm VarLdTmFact  CostPerHr;
/                          m³           SD           min      min/m³       $/hr
SUBTYPE   Loader S936E     2           0.05          0.40      0.05          90;
SUBTYPE   Loader S950E    2.4          0.04          0.43      0.035        130;
```

The characterized resource type *Truck* is defined with eleven properties, which include the truck's nominal capacity (m^3), the truck's mass when empty (kg), the truck's engine power (W), the transmission efficiency, the truck's retarding power (W), the truck's maximum speed (converted from km/hr to m/sec), the standard deviation of the truck's speed over its calculated speed, the truck's dump time (min), the time to maneuver into loading position (min), the truck's hourly cost ($/hr), and the time needed to cross the basic one-way bridge (min). The two types of trucks for this project, *S769C* and *S773B*, are defined as subtypes of *Truck* and their numerical properties are those shown in Table 2.

```
CHARTYPE Truck       Cap  EMass  Powr   Eff RetPowr MxSpd  SpdV DmpT MvT CstHr XTm;
/                    m³    kg    watts   %   watts  m/sec  SD   min  min $/hr  min
SUBTYPE  Truck S769C 23.6 31178 336000 0.82 434000 75/3.6 0.03 1.0  0.6  230  1.5;
SUBTYPE  Truck S773B 34.1 39396 485000 0.84 526000 62/3.6 0.02 1.12 0.72 300  2.5;
```

The following statement defines the SaveProps *AmtLoaded*, *RollRes*, and *Grade*, for the characterized type *Truck*. In contrast to the static properties defined above and which have the same values for all resources of the same subtype, SaveProps store properties whose values for each *Truck* can be changed while the simulation is running and which can have different values from one *Truck* to the next.

```
SAVEPROPS Truck AmtLoaded RollRes Grade;
```

The SaveProp *AmtLoaded* stores the amount of soil currently loaded into the *Truck* (m^3), the SaveProp *Grade* stores the grade for the road segment that the *Truck* is currently on, and the SaveProp *RollRes* stores the rolling resistance of the surface of the *Truck's* current road section.

3.2 Loading the Trucks—Determining the Amount Loaded and the Time Needed

The process by which a loader fills a truck with soil is modeled in detail by using STROBOSCOPE's built-in resource drawing facilities and the above engineering properties of the characterized resources *Loader* and *Truck*. The loading process begins with the creation of a new instance of activity *Load* and continues by drawing the appropriate resources through its incoming links, TR1, LD1, and SL1.

To create a new instance, activity *Load* checks its three incoming links TR1, LD1, and SL1, and creates a new instance when the ENOUGH attributes of all three incoming links return the value 1 (true). In this model, the ENOUGH attributes for the links TR1, LD1, and SL1, are not specified explicitly and have the default expressions that return the current contents of their preceding queues. Thus, activity *Load* can create a new instance whenever all three preceding queues are not empty.

Once a new instance of activity Load is created, it starts drawing resources from the preceding queues through its incoming links TR1, LD1, and SL1, in the order these links are defined in the simulation model, as indicated by the superscripts in Figure 1. Link TR1 has the default behavior and draws the *Truck* at the front of the FIFO queue *TrucksWait*. Similarly, link LD1 draws the *Loader* at the front of the FIFO queue *LoadersWait*. After a specific *Truck* and a specific *Loader* have been drawn into the new instance of activity *Load*, link SL1 starts the process of drawing soil from the queue *SoilToMove*. The order in which links draw resources is important because the statements for drawing the generic resource *Soil* through link SL1 make references to the properties of the specific *Truck* and the specific *Loader* that are already inside the new instance of *Load* and which must have been drawn earlier through links TR1 and LD1.

The following DRAWUNTIL and DRAWAMT statements allow link SL1 to draw multiple times, each time transferring a different amount of *Soil* from queue *SoilToMove* to the new instance of activity *Load*. Drawing through link SL1 continues until the amount of *Soil* deposited into *Load* is within half of the *Loader*'s bucket from the *Truck*'s capacity. Note that the *Truck* and the *Loader* in the following statements are the specific equipment that must have already been drawn into the new instance of activity *Load*.

```
DRAWUNTIL SL1 'Load.Soil.Count >= Load.Truck.Capacity - Load.Loader.BucketSize/2';
```

The volume of soil (m^3) drawn each time by link SL1 equals the nominal bucket size (m^3) of the specific *Loader* that is inside the new instance of activity *Load* multiplied by its random load variability.

```
DRAWAMT SL1 'Load.Loader.BucketSize * Normal[1,Load.Loader.LoadVariability]';
```

After each time link SL1 draws and transfers a bucketful of *Soil* (whose volume is *S* and is given by the variable SL1.LastAmtDrawn), it samples the corresponding time that it takes the *Loader* to fill its bucket with an amount of *Soil S* and load the *Truck*. This time is sampled by the statement below and is stored into the statistics collector of link SL1 to be used later to set the duration of the new instance of *Load*. This sampled time to load a bucket (the draw duration) depends on the properties of the *Loader* and has a fixed time component as well as a variable time component that depends on the specific amount of *Soil S* that was drawn last.

```
DRAWDUR SL1 'Load.Loader.FixedLdTm + SL1.LastAmtDrawn * Load.Loader.VarLdTmFact';
```

The duration of the new instance of activity *Load* is set equal to the time needed by the specific *Truck* inside this instance to maneuver into loading position plus the sum of the draw durations that were sampled by link SL1 and which represent the total time it takes the *Loader* to load this *Truck*.

```
DURATION Load 'Load.Truck.MvT +SL1.SumDrawDur';
```

Before the new instance of activity *Load* ends, it releases its *Truck* through link TR2 which stores in the *Truck*'s SaveProp *AmtLoaded* the amount of *Soil* in the terminating instance of *Load* (for later use).

```
ONRELEASE TR2 ASSIGN AmtLoaded Load.Soil.Count;
```

3.3 Engineering Calculation Formulas for Determining the Truck’s Speed

In addition to static properties and dynamic SaveProps, characterized resources can also have VarProps. These are formulas that are defined at the level of a characterized type, such as *Truck*, and which have direct access to the specific properties and SaveProp values of each characterized resource of type *Truck* (similar to object methods). The definition of the following five VarProps for the characterized type *Truck* streamline the engineering calculations needed to determine a *Truck*’s speed and the time it needs to traverse a road segment based on the segment’s length, grade and rolling resistance characteristics.

Each *Truck* stores the grade and the rolling resistance for its current road segment in the SaveProps *Grade* and *RollRes*. The VarProp *EffectiveGrade* is a formula that sums the SaveProps *Grade* and *RollRes* and gives the effective road resistance that is needed for subsequent calculations.

```
VARPROP Truck EffectiveGrade 'RollRes + Grade';
```

It should be noted that a road surface can have so much rolling resistance that its effective grade can be positive, even when the road segment is descending and has a negative grade. In this case, the *Truck*’s engine power must overcome the effective grade as if the *Truck* is traveling uphill.

The required *Truck* effective power depends on whether the effective grade for the current road is positive or negative and is given by either the *Truck*’s engine power or the *Truck*’s retarding power.

```
VARPROP Truck EffectivePow 'EffectiveGrade>=0 ? Powr*Eff : RetPowr'; /Watts
```

The *Truck*’s total mass includes its own mass when empty *EMass* (kg) plus the mass of the loaded soil, which equals its volume *AmtLoaded* (m^3) times the *SoilDensity* (kg/m^3). The absolute value of the road’s effective grade determines the force (in Newtons) that the *Truck*’s effective power (either its engine power or its retarding power) must overcome to move the *Truck*’s total mass either up or down the effective grade.

```
VARPROP Truck Force '(EMass+AmtLoaded*SoilDensity)*Abs[EffectiveGrade]*9.8';/Newton
```

The *Truck*'s speed (m/sec) is given by the *Truck*'s effective power divided by the force that the *Truck* must overcome to move, and the resulting speed must not exceed the *Truck*'s maximum speed. The calculated speed is then multiplied by the speed variability for that *Truck*.

```
VARPROP Truck Speed    'Min[EffectivePow/Force, MxSpd]';
VARPROP Truck SpeedVar 'Speed * Normal[1,SpdV]';
```

The above five VarProps for the characterized type *Truck* provide a series of easy-to-understand calculations, where each formula builds on the formulas before it, and which start with the grade and rolling resistance of the *Truck's* current road segment and which culminate with the determination of the *Truck*'s speed on that segment. These VarProps are used, one after another, each time the *Truck*'s speed is calculated to determine the time needed for the *Truck* to traverse the length of the current road segment.

3.4 Determining the Truck's Speed and Travel Times for Each Road Segment

The three *Truck* SaveProps *AmtLoaded*, *Grade*, and *RollRes*, provide the input for calculating the *Truck*'s speed and must be updated each time they change. As described earlier, the volume of soil loaded into each *Truck* (m^3) is random and is stored in its SaveProp *AmtLoaded* when the *Truck* flows through link TR2. The SaveProp *AmtLoaded* is reset to zero after the *Truck* dumps and flows through link TR8.

```
ONRELEASE TR2 ASSIGN AmtLoaded Load.Soil.Count;
ONRELEASE TR8 ASSIGN AmtLoaded 0;
```

The current road properties are assigned to the *Truck*'s SaveProps *Grade* and *RollRes* each time the *Truck* flows through the links TR2, TR5, TR8, and TR11. The following statements are for TR2. The statements for links TR5, TR8, and TR11, are similar.

```
ONRELEASE TR2 ASSIGN RollRes      0.07;
ONRELEASE TR2 ASSIGN Grade       -0.04;
```

With the above data it is possible to calculate the duration of activity *HaulToBridge* (min) which equals distance over speed (converted from seconds to minutes).

```
DURATION HaulToBridge 'DistSourceToBridge / HaulToBridge.Truck.SpeedVar / 60'; /min
```

The durations of activities *FinishHaul*, *ReturnToBridge*, and *FinishReturn*, are computed using similar ONRELEASE and DURATION statements.

3.5 Dumping Soil at the Dam Embankment

The number of *Trucks* that can dump at the same time is determined by the number of available resources of type *Spotter*. For this example, there is only one *Spotter*, and thus activity *Dump* can have only one instance at a time. Additional *Trucks* wait in the FIFO queue *WaitToDump*. The duration of the instance of *Dump* depends on the subtype of *Truck* that is currently dumping.

```
DURATION Dump Dump.Truck.DumpTm;
```

Because each *Truck* stores the amount of *Soil* it carries in its SaveProp *AmtLoaded*, there is no reason for the generic resource *Soil* to flow through the network. When an instance of activity *Dump* terminates, link SL2 creates an amount of *Soil* equal to the *Truck*'s *AmtLoaded* and releases it into the queue *SoilMoved*.

```
RELEASEAMT SL2 'Dump.Truck.AmtLoaded'
```

It should be noted that because the above statement references the *Truck* inside the terminating instance of Dump, link SL2 must be defined in the model before link TR8. This way, link SL2 can create and release the resource *Soil* first, before the terminating instance of *Dump* releases its *Truck* through link TR8.

4 SIMULATION RESULTS

4.1 Simulation Results when using One One-Way "Slow" Bridge

The simulation model described above was run for several numbers of S769C and S773B trucks and one one-way bridge that can support one truck at a time. The bridge was also "slow" in that each truck must cross slowly and take the time shown in Table 2 depending on its type. Figure 2 shows the average Total Cost over 10 replications for each combination of trucks when having one one-way "slow" bridge and using the *common random numbers* variance reduction technique (Ioannou and Martinez 1996b).

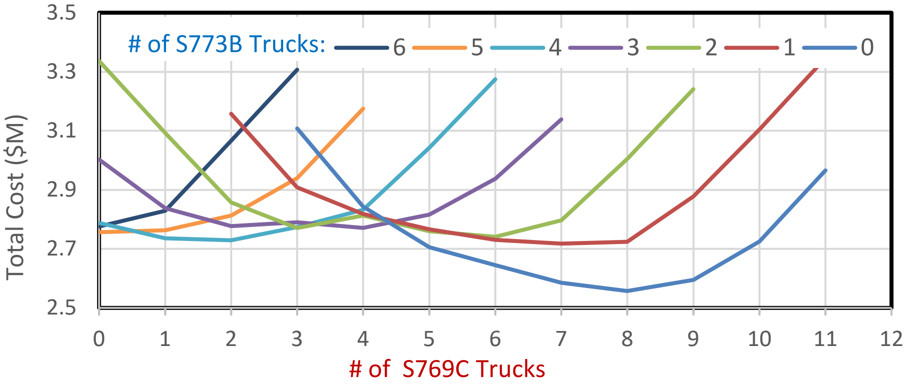

Figure 2: Total earthmoving cost when using one one-way "slow" bridge.

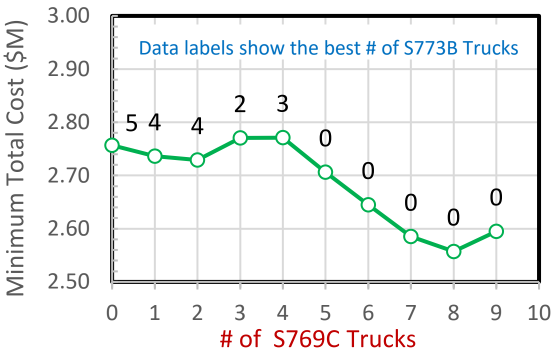

Figure 3: Minimum total cost vs S769C trucks when using one one-way "slow" bridge.

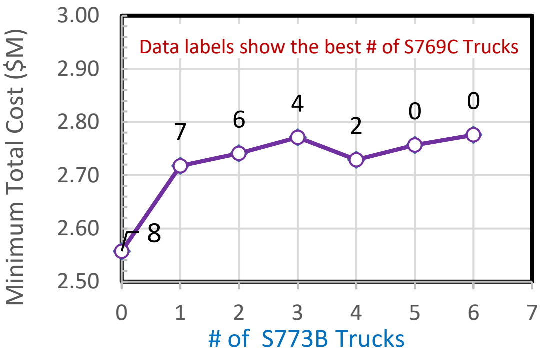

Figure 4: Minimum total cost vs S773B trucks when using one one-way "slow" bridge.

Figure 3 shows that when having one one-way "slow" bridge, the combination of eight S769C trucks and zero S773B trucks produces the minimum Total Cost of $2,557,256. This is not unexpected because having a uniform fleet of equipment in these types of earthmoving projects often produces the best results.

Figure 4 shows that when one or more S773B trucks must be used on the job (for example, because they are already available), the best combinations are significantly more expensive and result in minimum Total Costs between $2.7 and $2.8 million.

4.2 Simulation Results when using Two One-Way "Slow" Bridges

Figure 5 shows the STROBOSCOPE simulation network for a model that uses two one-way "slow" bridges (like the one above), each dedicated to one direction of traffic. Figure 6 shows the average Total Cost for several combinations of the numbers of S769C and S773B trucks obtained from 10 simulation replications for each truck combination using the *common random numbers* variance reduction technique. Figure 7 shows that having eleven S769C trucks and zero S773B trucks produces the minimum Total Cost of $2,392,632, which is $164,624 less than when using one one-way "slow" bridge. Thus, if the second one-way "slow" bridge costs less than $164,624, it is better to deploy two "slow" bridges and have two-way traffic instead of having just one "slow" bridge alternating between traffic directions.

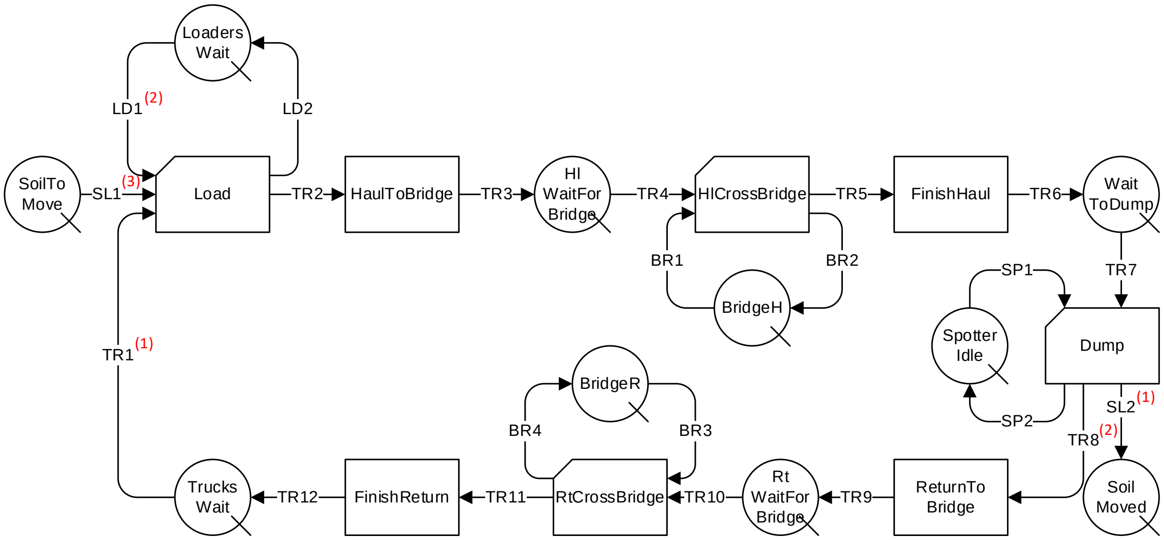

Figure 5: STROBOSCOPE network for dam construction simulation model using two one-way bridges.

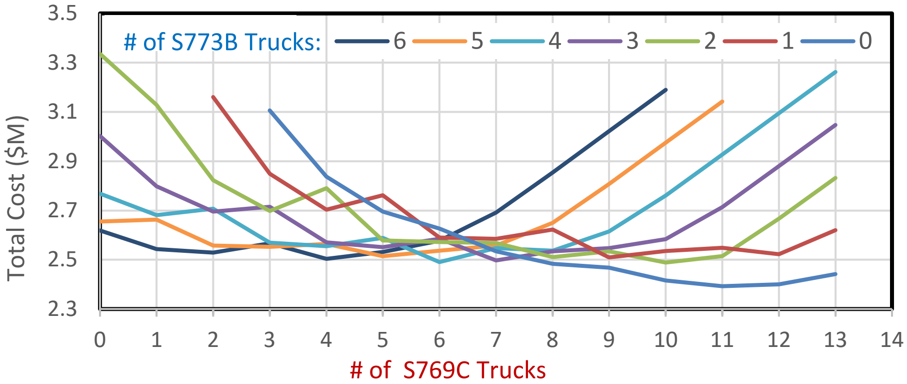

Figure 6: Total earthmoving cost when using two one-way “slow” bridges.

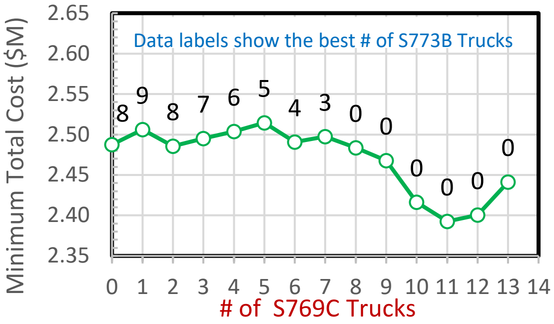

Figure 7: Minimum total cost vs S769C trucks when using two one-way “slow” bridges.

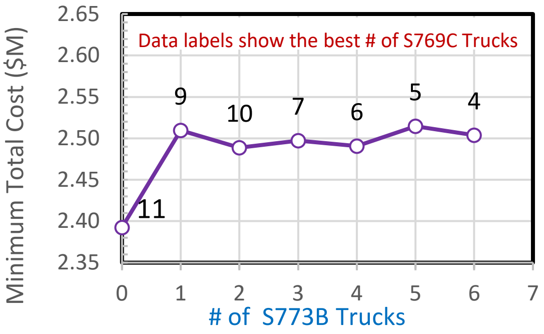

Figure 8: Minimum total cost vs S773B trucks when using two one-way “slow” bridges.

Figure 8 shows that if one or more S773B trucks must be used on the job, the best combinations are significantly more expensive with minimum Total Costs around $2.5 million. However, even these inferior combinations of S769C and S773B trucks cost less than the minimum Total Cost of $2,557,256 when using one one-way “slow” bridge. This shows that having two one-way “slow” bridges, each dedicated to one direction of traffic, is the superior alternative.

4.3 Simulation Results when using Two One-Way “Fast” Bridges

Simulations were also run for combinations of the numbers of S769C and S773B trucks when having two bridges, one for each direction of traffic, that can support any number of trucks crossing at high speed. The average Total Costs when using two “fast” bridges resulting from 10 replications and using common random numbers are shown in Figure 9. Figures 10 and 11 show that the best combination in this case uses zero S769C trucks and eight S773B trucks and produces a minimum Total Cost of $2,078,575. This is $314,057 less than when using two “slow” bridges. Thus, increasing the speed of crossing and the number of trucks that can be on each bridge at the same time produces considerable cost savings by streamlining truck traffic. Clearly, switching from two “slow” bridges to two “fast” bridges should be pursued if the extra cost is less than $309,479. Note also that when using two “fast bridges”, the best combination of trucks no longer uses S769C trucks and has now switched to using only eight of the larger S773B trucks.

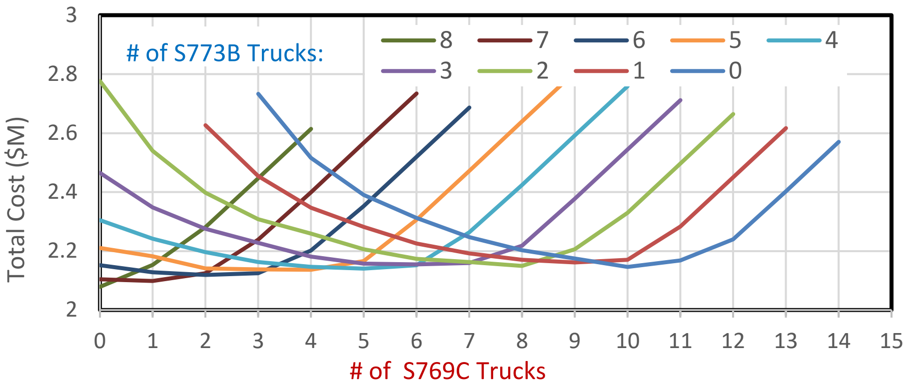

Figure 9: Total earthmoving cost when using two one-way “fast” bridges.

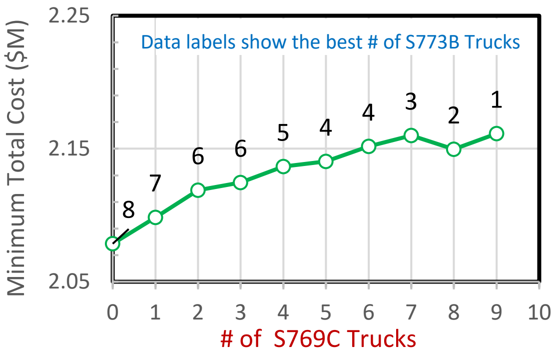

Figure 10: Minimum total cost vs S769C trucks when using two one-way “fast” bridges.

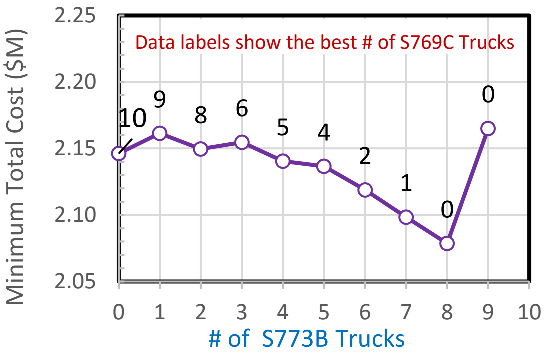

Figure 11: Minimum total cost vs S773B trucks when using two one-way “fast” bridges.

4.4 Decision Table

Table 4 shows a summary of the optimum truck choices depending on the costs of the bridge options:

- C1 = cost of the first slow bridge.
- C2 = cost of the second slow bridge.
- CF = cost of the two fast bridges.

Table 4: Optimum truck alternatives given cost of slow and fast bridge options.

C2:	C2 > $164,624		C2 < $164,624	
CF:	CF>$478,681+C1	CF<$478,681+C1	CF>$314,057+C1+C2	CF<$314,057+C1+C2
Bridge(s):	1 Slow Bridge	2 Fast Bridges	2 Slow Bridges	2 Fast Bridges
Min cost:	$2,557,256 + C1	$2,078,575 + CF	$2,392,632 + C1 + C2	$2,078,575 + CF
Trucks:	8 x S769C	8 x S773B	11 x S769C	8 x S773B

5 MODEL ANIMATION

Figure 12 shows a snapshot of the animation that was developed to verify and validate the simulation model, to investigate its properties, and to present the results to others. Animations were developed for different combinations of S773B and S769C trucks as well as for crossing the river using one or two one-way one-truck "slow" bridges or two one-way multi-truck "fast bridges". These animations showed clearly that having a separate bridge for each direction of traffic improved system performance significantly.

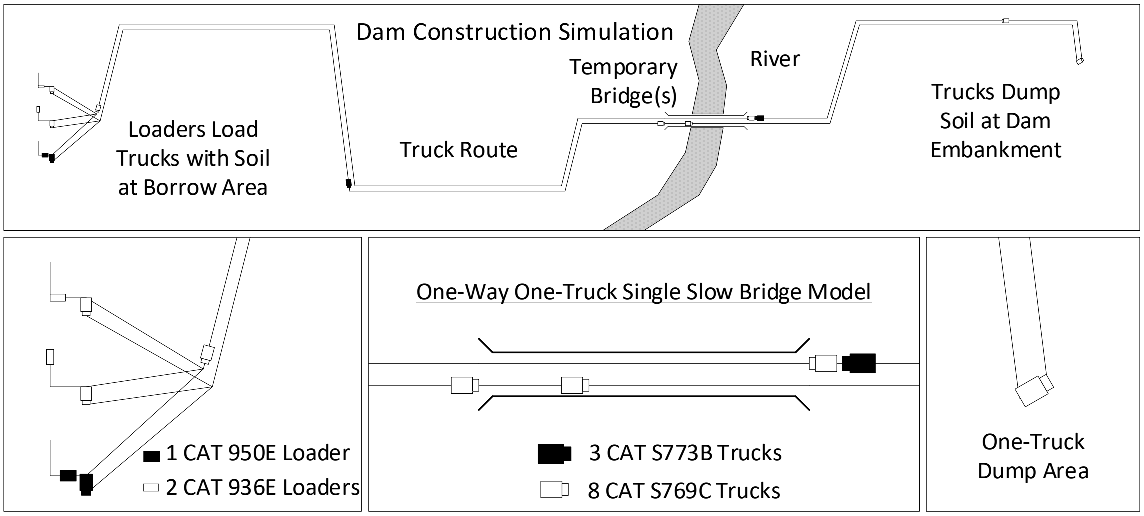

Figure 12: Earthmoving for dam construction—animation model snapshot.

6 CONCLUSION

The simulation model presented in this paper illustrates the application of the engineering calculations typically used for operations planning and equipment selection in heavy construction to estimate performance and project costs before construction begins based on project characteristics such as the grade and rolling resistance of the haul and return roads and the mechanical properties of actual models of heavy loaders and trucks. Sensitivity analysis estimated the total project cost for various combinations of S773B and S769C trucks to find the best combination of equipment that maximizes performance. The incorporation of project-specific factors such as the effects on traffic and project cost of crossing a river along the haul route using one or two "slow" or "fast" temporary bridges was also investigated and showed that the minimum project cost and the corresponding optimum type and number of S773B and S769C trucks change depending on the cost of the bridges. The simulation model presented in this paper can serve as a template that can easily be adapted to other projects to help facilitate the wider acceptance of simulation in heavy construction practice.

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