

EFFECTIVE SIMULATION OF EARTH MOVING PROJECTS

Jamal Siadat
Janaka Y. Ruwanpura

University of Calgary
2500 University Dr. N.W.
Calgary, T2N 1N4, CANADA

ABSTRACT

In the context of earth-moving (EM) projects, process-based simulation platforms have demonstrated their effectiveness in predicting project durations, costs, and resource requirements. However, these simulators are developed by simulation expert using advanced programming techniques. Therefore, understanding the details of these models or enhancing them to fit a particular purpose can be a daunting task. This paper presents Earth-Sim, an EM template developed using the SimFC simulation platform. Earth-Sim mimics the behaviors found in an earlier version of the SIMPHONY EMS template. SIMPHONY EMS was chosen because a) it is a well-recognized template which models all activities within the EM process; and b) it has been validated against data obtained from construction job-sites. This paper explains how Earth-Sim was developed solely using the common elements found in SimFC without any programming. Furthermore, the results obtained from Earth-Sim are compared against results from SIMPHONY EMS to illustrate the validity of the outputs.

1 INTRODUCTION

EM is the process of moving soil from one location to another. EM projects are generally large projects and full of uncertainties where expensive equipments continually have complex interactions. Therefore, planning EM projects is difficult and has been the subject of various studies. One of the most important factors in planning EM projects is to have a complete and accurate understanding of the project scope and required resources. Since these variables are not determined in the estimation phase, using stochastic estimates in a controlled environment would allow the planners to experiment with various activity sequences, allocation of man-power, equipment needs, material, and other elements of the project. By analyzing different scenarios, a planner can produce a schedule that is optimized for the given project by not only incorporating traditional planning elements but also accounting for many unknowns. As a result, it has been argued that simulating EM operations would allow construction planners and estimators to reasonably predict the overall duration, resource requirements as well as cost considerations (Halpin 1992).

Despite the advantages of computer simulation to model construction projects, conducting simulations for construction projects is rarely performed outside of academics and the main reason is attributed to the complexity of simulation methodologies (Martinez 1998; AbouRizk and Hajjar 1998). These complexities are generally manifested in terms of the required expertise to interact with simulation platforms as many construction simulation platforms require users to be intimately familiar with both simulation concepts and programming languages. Therefore, the use of these platforms is rather difficult for most planners and estimators. This is one of the reasons why some (e.g., AbouRizk and Hajjar 1998) promoted the use of special purpose simulators for construction purposes as special purpose simulators are more user friendly and require very little training for the end-users. However, it was quickly realized that special

purpose simulators also require significant investments to develop and therefore, the concept of unified modeling methodology was introduced by (AbouRizk and Hajjar 2002). This approach allows end-users to take advantage of the simulation engine or user interface specification capabilities to create special purpose simulators for construction projects. While this approach results in a significant reduction in development time, it still requires the involvement of simulation experts to create custom components based on user requirements resulting in initial cost and time investments.

On the other hand, time constraints heavily influence the activities involved in planning and estimating construction projects and therefore, developing and validating special purpose simulation models under tight timelines may not be a viable approach (Mohamed and AbouRizk 2006). As a result, project planners and estimators have no choice but to rely on historical data, expert opinion and traditional CPM-based schedules which given the uniqueness of each project may produce less than optimum results.

In order to address the mentioned shortcomings, a general purpose Simulator for Construction (SimFC) purposes has been developed. The main goal of SimFC is to improve the user experience as much as possible without limiting user's ability to freely define models or create special purpose simulation templates. The research presented in this paper highlights some of the strides taken in achieving this ambitious goal. The main objective of this study is to highlight SimFC's ability to create special purpose simulators without any programming by the user. This is illustrated through the implementation of an EM special purpose simulator called Earth-Sim. The sub-objectives of this work can be summarized as:

- To present a conceptual method for designing and implementing special purpose simulators
- To create Earth-Sim as a special purpose simulator for EM projects; and
- To define a specific EM scenario using Earth-Sim and compare the outputs against the outputs produced by another special purpose simulator to ensure the validity of the results

The remainder of this paper is structured as follows. Section 2 presents the various approaches developed to simulate EM projects. Section 3 presents an in depth look at the EM process. Section 4 describes SIMPHONY EMS as one of the accepted special purpose simulators to model EM in construction. Section 5 discusses the required steps to create the Earth-Sim special purpose simulator within SimFC. Section 6 presents a simple EM example which was implemented both in Earth-Sim and SIMPHONY EMS and compares the generated results. Finally, the concluding remarks are added in section 7.

2 EXISTING APPROACHES TO MODEL EM OPERATIONS

Developing models to effectively represent EM operations has been of interest to construction simulation researchers for some time. These models range from simple static models to complex approaches where the model may be enhanced through the development of custom components.

One of the earliest attempts to model EM operations is discussed in (Oloufa 1990). The work illustrated the need for a construction simulation approach based on the unique requirements of construction in comparison to manufacturing. An EM simulator is discussed where various components can communicate via "messages". Furthermore, the behavior of a given specific scenario through simulation is displayed with the aid of animated computer graphics. Shi and AbouRizk developed a Resource-Based Modeling system for EM operations (RBM-earth); (Shi and AbouRizk 1998). Resource-based modeling allowed users to specify properties for construction operations. These properties were defined using atomic models. Each atomic model represented an operation that an equipment can perform. Like many of the earlier studies in this field the main goal was to develop a simulator where little programming would be required by the end user.

Hajjar and AbouRizk developed AP2-EARTH as a special purpose simulation platform designed to model EM projects (Hajjar and AbouRizk 1997). Various real-world elements such as source site, roads and trucks along with their properties were accurately represented in AP2-Earth and a case study involving a mining operation was used to validate the results produced by this simulator. SIMPHONY was developed as an environment which eased the development of special purpose simulators and therefore, reduced the initial investment cost (Hajjar and AbouRizk 1997). SIMPHONY provided an environment to

build various special purpose simulators and AP2-EARTH was one of the redeveloped models in SIMPHONY which illustrated the benefits of using the unified model methodology (Hajjar and AbouRizk 1997; Hajjar and AbouRizk 2002).

The Earthmoving Equipment Selection and Estimation Tool (EESSET) was developed as a knowledge-based expert system which contained information obtained from various experts in the EM domain (Xie 1997). Initially, the project criteria and working conditions were entered using defined interfaces and with the help of EESSET, the users were able to select appropriate fleets of equipment based on the entered criteria. A web-based special purpose EM simulator was developed by Sawhney et al. using the Java based SILK simulation engine (Sawhney et al. 1999). The benefit of this approach was that the user can manage the simulation from a remote location. Using STROBOSCOPE (Martinez 1994), Martinez developed the special purpose EARTHMOVER simulator which was used to model EM operations (Martinez 1998). Similar to AP2-EARTH, it contained a set of graphical elements representing various activities and equipment.

Marzouk developed SimEarth which utilized computer simulation in conjunction with genetic algorithms (Marzouk 2002). The genetic algorithm was used to search for the best fleet selection which would minimize the project total cost, while considering the quantity and type of available resources. In a later work (Marzouk and Moselhi 2003), the results generated by SimEarth were compared to results generated by the Caterpillar software (FPC) and it was argued that SimEarth represented EM uncertainties in a more reliable manner.

Based on the assumption that only scrapers are used for the EM operation, (Neil and Mayfield 2005) developed a spreadsheet application to select an optimal set of scrapers given the project budget and time constraints. (Montaser et al. 2012) developed a process which uses Global Positioning Systems (GPS) to track machinery and equipment during project execution. Best fit algorithms are then used to determine the best distribution to represent the actual productivity and travel times obtained from GPSs and entered into a simulation model. Finally, the simulation is executed to determine the expected project duration. This method can serve as an early warning system helping project managers in taking timely corrective actions based on real-time data. More recently Cheng, et al. presented a Petri-net simulation model to represent EM projects (Cheng et al. 2011). Similar to many of its predecessors, the model considers various factors that influence the EM operation such as equipment availability, costs and predicts the project duration, resource utilization rates as well as the project costs. The results generate by the platform were validated against results obtained from a high-rise construction project in China.

All the mentioned approaches do provide powerful mechanisms to model EM operations, however; the creation and development of special purpose simulators require a relatively large investment, especially in terms computer of programming. This will inevitably result in higher costs and prolonged development times with potentially significant testing requirements. The problem can be exacerbated if new elements need to be introduced to a model after the initial model development and delivery or if simple behavioral changes are required (since changes will require an understanding of the original design choices and base code, and in many cases this knowledge only resides with the original developer). A special purpose simulator that is based exclusively on an easy to use general purpose GUI will alleviate all programming requirements and simplify any potential maintenance activities.

3 THE EM PROCESS

As mentioned, EM is a process occurring in many construction projects where substantial quantities of soil are moved from a location (source) to another (placement or dumpsite). Site-leveling at earlier stages of construction, removal of excess soil due to mining and tunneling operations and pond/lake constructions are all examples of EM processes requiring a level of soil displacement. Although EM is a fairly standardized process, the developed models exhibit slight variations which can be attributed to the scope of the model as well as the model's level of abstraction. Since the goal of this work is to mimic the behav-

iors found in the well known SIMPHONY EMS special purpose simulator, the EM process described in this section is consistent with the description found in (Hajjar and AbouRizk 1997).

EM projects are comprised of five main processes. These are (1) excavating, (2) loading, (3) hauling, (4) unloading; and (5) spreading. Excavating refers to all operations conducted prior to loading. This generally includes digging the ground and placing the soil in specific locations to create various piles. Loading refers to the process of placing the soil from piles onto the transport vehicles. Hauling refers to transporting the soil from the source to the dumpsite. The method used for hauling usually depends on the proximity of the source to the dumpsite. For example if the source and dumpsites are very close, bulldozers or even wheelbarrows might serve as ideal transportation mechanisms. However, it is safe to assume that trucks are the most common transportation mechanisms nowadays. The time required for a truck to haul the soil to the dumpsite and back (otherwise known as the truck cycle time) is comprised of the load time, travel time, the unloading time and the return time. To obtain a better measure of truck travel times, the travel paths are divided into distinct segments where each segment would have similar properties including traffic congestion and rolling resistance. This information is combined with the manufacturer specified data for truck speeds on various terrains to obtain the time spent at each segment. Unloading refers to the process of emptying the transport vehicles at the dumpsite. The unloading time for each truck type is determined using historical data. Finally, spreading is the process which creates layers of soil at the dumpsite so that more soil can be placed there if needed. The duration of spreading is determined using historical data as well.

In any EM process, there are several key factors which affect the EM process. These are (1) the location of the source and dumpsites as the distance will affect the hauling time, (2) the quantity of soil to be displaced; and (3) the road conditions. The choice and number of equipment is generally affected by the above factors as well as the schedule considerations. Although the EM process is fairly straight forward, complexities arise when several EM projects are executing concurrently.

4 SIMPHONY EMS

AP2-Earth was one of the first special purpose simulators developed to model the EM process. It was also one of the first templates validated against data obtained from an actual jobsite. Therefore, it was argued that AP2-Earth can be used as a basis for estimating project duration and resource requirements (Hajjar and AbouRizk 1997). Unfortunately, the AP2-Earth platform is no longer available; however, it was implemented as a special purpose simulator in SIMPHONY LEGACY called SIMPHONY EMS. Although this version of SIMPHONY has been officially phased out, the authors were able to obtain a copy which also contained the SIMPHONY EMS template. The remainder of this section describes SIMPHONY EMS along with the various elements contained within it.

SIMPHONY EMS is comprised of 16 elements built in a hierarchical fashion. Table 1 illustrates a list of 11 elements along with the user-defined properties defined for each. The remaining 5 elements do not have any user defined properties and are therefore excluded from the table. The overall parent element is EMS and is used to enable information exchanges between the various sub elements. Source, Placement, Truck, Road, Traffic Split and Intersection are the next level of elements in the hierarchy. Source and Placement represent the source and dump sites respectively. As illustrated in Figure 1, Source may contain Dozer, Pile, Preparation, Excavator, In and Out elements. The Placement element is illustrated in Figure 2 and it may contain any of the Dump, Dozer, Pile, Spreading, Dozer, In and Out elements. The next subsection will discuss the details for each of the components along with their interactions.

4.1 EM Model Specification Mechanism

In order for a user to define specific models using SIMPHONY EMS, a user must understand the simulation behavior of each of the mentioned elements within the simulator. This subsection describes the simulation behavior of each of elements along with their interactions.

In SIMPHONY EMS, Trucks are the main entities for any model and they should be connected to a source element. The In element is used to transfer entities to the Source or Placement sub elements. Similarly, the Out element is used to transfer entities out of the Source or Placement elements. A user specifies the overall amount of soil to be loaded from a particular Source element by specifying the AmountToHaul variable. The overall amount of soil which has been moved from the Source is tracked using an internal AmountLoaded variable and is updated as soon as a truck is loaded (as previously mentioned Table 1 only contains user-defined attributes, therefore, AmountLoaded is omitted from Table 1).

Table 1: SIMPHONY EMS elements and their properties.

Element	Property	Type
Truck	DumpingTime Priority (Priority at intersections and loading) Path (Path number to follow on branches) Capacity Quantity Type	Distribution Number Number Number List
Source	AmountToHaul	Number
Dozer	Productivity Quantity	Distribution Number
Pile	StartingAmount	Number
Excavator	Productivity Quantity	Distribution Number
Dump	Quantity (number of available locations per dumpsite)	Number
Road	GradeResistance RoadResistance Length	Number Number Number
Traffic	First Between Priority (Priority at intersections and loading)	Number Distribution Number
Split	PathNumber	Number
Intersection	Delay	Distribution

Dozer element is used to create a number of user specified equipment used for preparation of source sites or spreading activities at the dumpsites. In terms of modeling, they are entities which are created and destroyed in the Source or Placement elements with specific properties. The Pile element represents the amount of soil which is ready to be transported from a source location or the soil which has been placed at a dumpsite. A user-defined attribute StartingAmount, and an internal simulator defined attribute CurrentAmount, are specified within Pile. At the source site, if a truck's capacity is greater than the CurrentAmount, then the truck is queued until more soil is prepared from the proceeding Preparation element and added to the pile. Otherwise, the CurrentAmount of the Pile is updated by subtracting by the truck's capacity from it. At the destination, the truck's capacity is added to CurrentAmount to represent the total unloaded amount of soil.

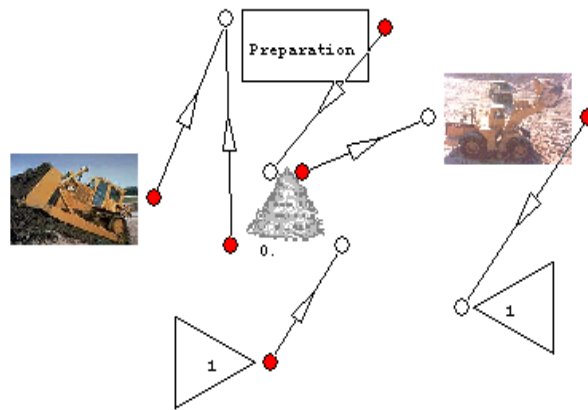


Figure 1: SIMPHONY EMS Source element and its sub components.

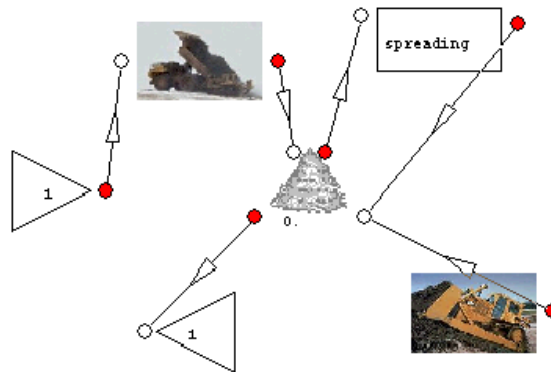


Figure 2: SIMPHONY EMS Placement element and its sub components.

Preparation represents all activities performed to prepare the soil piles. These activities are illustrated in Figure 3. If a pile has been already created or the user isn't interested in modeling those activities, the Preparation can be left out and instead the StartingAmount of the Pile element is set to the amount of available soil. Both a Dozer and a Pile element must be specified as inputs to Preparation. The output connection of Preparation must also be connected to a Pile element. Preparation contains 7 elements imported from SIMPHONY's common template. As mentioned, In is used to connect the output of the elements connecting to Preparation to the sub elements contained within it. A conditional branch is placed immediately after In which checks the internal AmountPrepared attribute against the user specified AmountToPrepare. If AmountPrepared is less, an adequate amount of soil has been prepared and the operation is terminated. Otherwise, the first execute element is executed which adds the Dozer's capacity to AmountPrepared. Next, a task element is used to update the duration of the truck entities based on the productivity rate of the Dozers. This duration is calculated by dividing the capacity of the dozer (in cubic meters) by the productivity rate (per hour) multiplied by 60 (to obtain the duration in minutes). Next, a second execute statement is executed which sets the payload of the dozer equipment to its capacity (in other words after the time in the previous task has elapsed, the dozer has reached its maximum capacity). Finally, the trucks are sent to the element connected to the outgoing connector of Preparation using Out.

Despite its name, the Excavator element represents loading the soil onto the trucks. The number of loading equipment and their productivity rates can be specified by the user. If the AmountLoaded variable of the parent Source element is less than AmountToHaul and a loading equipment is available, the truck is loaded up to its capacity. The loading duration is computed as the truck's capacity (in cubic meters) divided by the productivity rate (per hour) of the loading equipment multiplied by 60 (to obtain the duration

in minutes). The loading equipment is set to busy for the duration of this operation and the truck's capacity is added to the AmountLoaded variable of the Source element. If the Source parent's AmountLoaded variable is greater or equal to AmountToHaul, then no more soil should be moved from this source and no loading will be performed and finally, if no loaders are available the truck is placed in a queue and is served based on the truck's priority.

Four elements can be used to represent soil transportation activities between a source and a destination. These are the Road, Traffic, Split and Intersection elements. The speed of the trucks on each segment of the road can be obtained using manufacturer supplied information. In this implementation however, a Bell curve is defined to reasonably approximate the manufacturer supplied data (the original implementation in (Hajjar and AbouRizk 1997) creates best-fitted curves based on user-input data; however, SIMPHONY EMS uses a Bell curve). The overall time a truck spends on each road segment can be calculated by dividing the length of the road by the speed of the truck. As the name suggests, Intersection represents the road intersections. At these points only a single truck may pass and other trucks arriving at the same time are queued. Split represents the splits occurring in roads where a truck can either stay on the current road or take a different road. If a truck's Path parameter matches the PathNumber specified in the Split, the truck will change paths, otherwise it will stay on the current road. The Traffic element is used to model any background traffic occurring at intersections. Essentially, they are entities which must be connected to the Intersection element and destroyed after passing through the intersection.

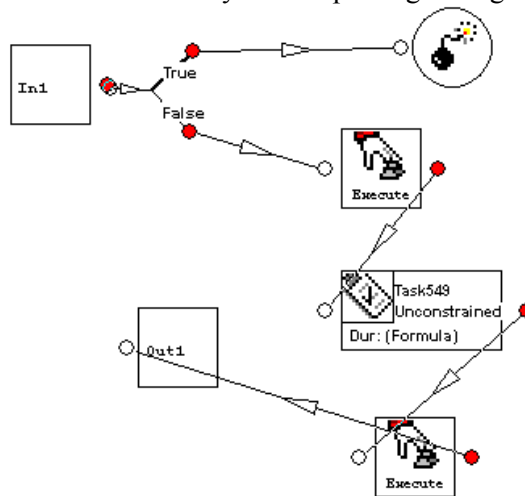


Figure 3: SIMPHONY EMS Preparation sub components.

The Dump element is used to represent the unloading activity at dumpsites. The number of dump locations is specified by the user and a higher number results in less truck wait times at the dumpsite. This element must be connected to the Pile element as the result of this activity is an increase to the pile sizes at dumpsites.

5 EARTH-SIM IMPLEMENTATION

The main goal of this exercise is highlight SimFC's ability to define special purpose simulators. In the context of this work, this is exhibited by re-implementing the above EM template in SimFC without any programming by the user. The remainder of this section illustrates how the SimFC common elements are used to create EM elements.

Upon mining requirements for creating and defining special purpose simulators, it was determined that two requirements are most crucial and must be addressed in an appropriate manner. First, based on the survey conducted by (AbouRizk, Halpin, and Lutz 1992), it is clear that users must have to ability to

modify the user interface by inserting pictorial images to represent operational activities (e.g., hauling) or entities (e.g., trucks). Second, the interface must have the ability to allow users to group several elements together and create various hierarchies to represent complex activities (such as Preparation in Source elements).

In order to address the above mentioned requirements, the SimFC common element library was expanded to include a template property. When selected, a file dialogue is presented which allows the user to select an appropriate image which is placed on the selected element. If the user doesn't select an image, a blank image will be used. SimFC already allows for grouping of multiple elements using the WBS element and no modifications to this element were required to address template creation concerns.

As for creating the EM template in SimFC (Earth-Sim), the approach was rather simple as virtually all of the SIMPHONY EMS elements were created by grouping a set of elements found in SimFC's common elements. For example the trucks were an entity with a set of entity attributes assigned to them. The duration of various activities which are computed using the capacity and productivity parameters, were inserted into SimFC's activity elements using Microsoft Word equations in a manner similar to (Siadat, Ruwanpura, and Siyadat 2012). Where required, elements were grouped together using the WBS element, and the required parameters were defined at the level and passed on to individual elements. For example the Road element in Earth-Sim (which is illustrated in Figure 4) is a WBS element comprised of 6 sub-components. Length, Road Resistance and Grade Resistance are the required parameters which are defined at the WBS level and passed on to the desired elements. The Road_IN element signifies the entity's entry point. Determine Payload is a conditional branch with two possible outcomes. If the truck's payload is greater than 0, the speed is approximated using the bell curve approximation for a fully loaded truck and if payload is 0 the speed is approximated using the bell curve approximation for an empty truck. The resulting speeds are saved in the Speed control variable. The duration that a truck spends on a road segment is then calculated using the length and speed parameters. Finally, the truck entity exits the road element using Road_Out. Note that all the computations used in Earth-Sim are obtained from SIMPHONY EMS.

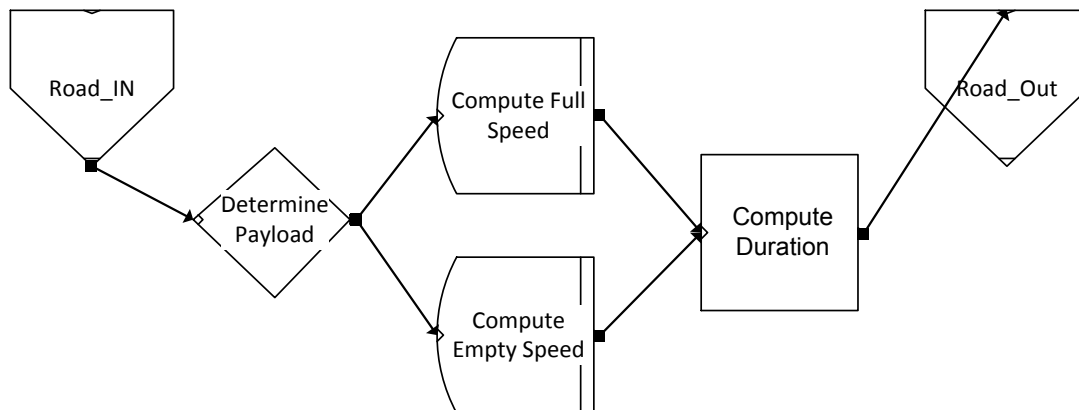


Figure 4: SimFC Road component and its containing elements.

6 AN EM EXAMPLE

A study comparing the outputs of Earth-Sim and SIMPHONY EMS was conducted to ensure that (a) similar to SIMPHONY EMS, Earth-Sim is capable of adequately modeling complex EM processes; and (b) the results generated by Earth-Sim are valid. Figure 5 illustrates the developed model which was implemented both in Earth-Sim and SIMPHONY EMS (however, the screenshot is from the Earth-Sim implementation). The subsequent subsections describe the details of the implemented model. It is noteworthy

that the naming conventions for SIMPHONY EMS elements are used to refer to the various elements of this example as well.

6.1 Site Layout

The model involves moving 20000 m³ of soil from a single source to a single dumpsite. The road connecting the source and destination areas is divided into 7 different segments with various lengths ranging from 98 meters to 410 meters and various grades. The properties for each of the road segments are illustrated in Table 2.

6.2 Equipment

At the source a single Dozer is used to prepare the soil at a rate of 950 m³ per hour and create the soil pile. An Excavator is then used at the rate 850 m³ per hour to place the soil from piles onto the trucks. Two truck types are used to haul soil from the source to the destination sites. The characteristics for each truck type are shown in Table 3. At the dumpsite a single Dozer is defined to spread the unloaded soil at the rate of 700 m³ per hour.

Table 2: Road segments and their properties.

Road Segment	Length (m)	Road Resistance	Grade Resistance
A	340	3	2
B	466	-1	-2
C	260	1	0
D	150	1	0
E	98	1	1
F	410	1	2
G	244	2	-1

6.3 Results

The discussed example was executed in SIMPHONY EMS over 100 iterations. The minimum duration was 1723.35 minutes and the maximum duration was 1726.68 minutes. The mean was 1725.44 minutes with a standard deviation of 0.71. The average roundtrip for the first truck (Komatsu model HD1200-1D) was 9.28 minutes while the average roundtrip for the second truck was 9.9 minutes. Finally, the average utilization rate of the excavator was computed to be 81.77%.

Figure 6 illustrates the sorted computed durations of the discussed model over 100 iterations executed using SimFC's Earth-Sim. The minimum and maximum durations were 1723.85 and 1726.53 minutes respectively. The mean was 1725.46 minutes with a standard deviation of 0.65. The average roundtrips for the first and second trucks were 9.45 and 9.85 minutes respectively and the average utilization rate of the excavator was computed to be 81.79%.

These results demonstrate that Earth-Sim outputs are consistent with the values generated by SIMPHONY EMS and therefore, Earth-Sim is a viable alternative to SIMPHONY EMS. It should be also noted that the total development time for Earth-Sim was less than 3 hours while the development time for SIMPHONY EMS and AP2-Earth were 28 and 400 hours respectively (Hajjar 1999). This shows that the SimFC method of creating special purpose simulators is not only statistically accurate but also does have the potential to significantly decrease development time as well.

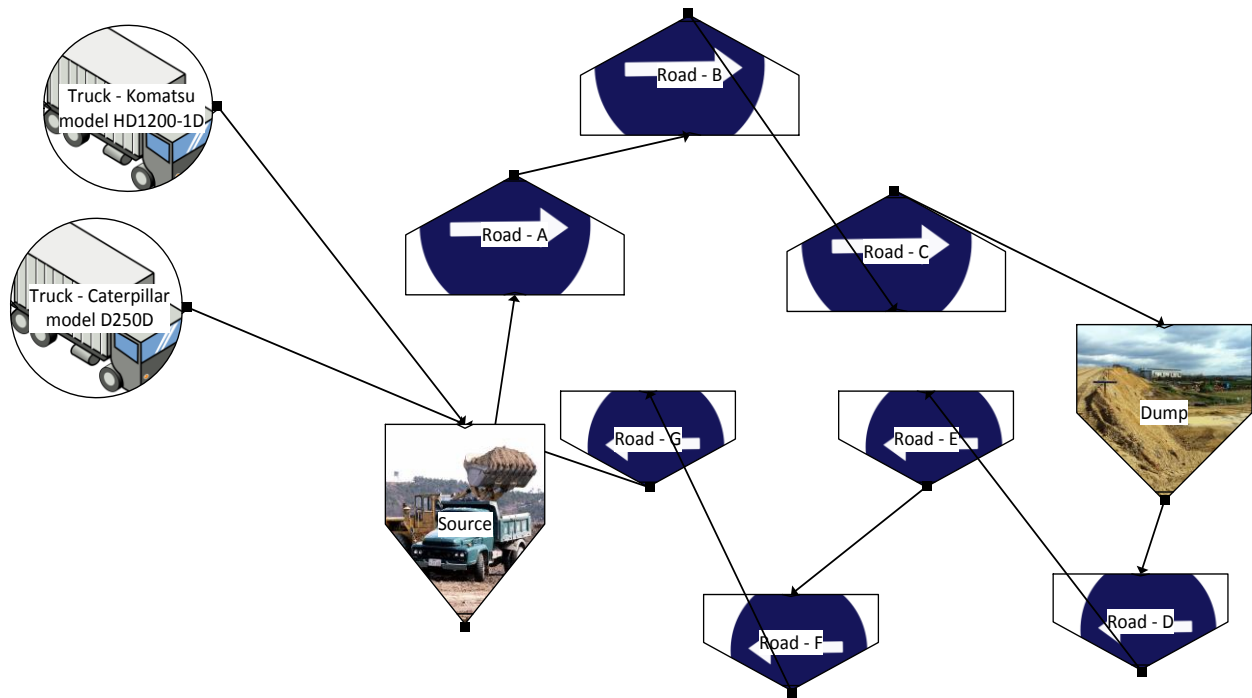


Figure 5: The developed EM example in Earth-Sim.

Table 3: Trucks entities used in the developed model along with their properties.

Truck Type	Capacity (m ³)	Dump Time (min)
Komatsu model HD1200-1D	75	Normal (1.42, 0.21)
Caterpillar model D250D	65	Normal (1.6, 0.15)

7 CONCLUSION

This paper presented a new approach to develop special purpose simulators for construction purposes using the general purpose SimFC simulator. This approach utilizes a library of common components to define new elements with specific behavior. Furthermore, the simulator definition mechanism allows the user to upload various images in order to improve the graphical user interface of the special purpose simulator.

In order to illustrate the effectiveness of the simulator creation mechanism in SimFC, the Earth-Sim EM template was developed. All considerations were made to ensure that Earth-Sim can adequately mimic the behaviors found in an earlier version of the SIMPHONY EMS template. Not only Earth-Sim was developed solely using the common elements found in SimFC and without any programming, the results obtained from Earth-Sim were virtually identical to the results obtained from SIMPHONY EMS. Furthermore, the total development time for Earth-Sim was significantly less than the development for SIMPHONY EMS and AP2-Earth. Given the encouraging results from this study, the authors have now moved to define more special purpose simulators in SimFC and compare them against other special purpose simulators developed in other platforms.

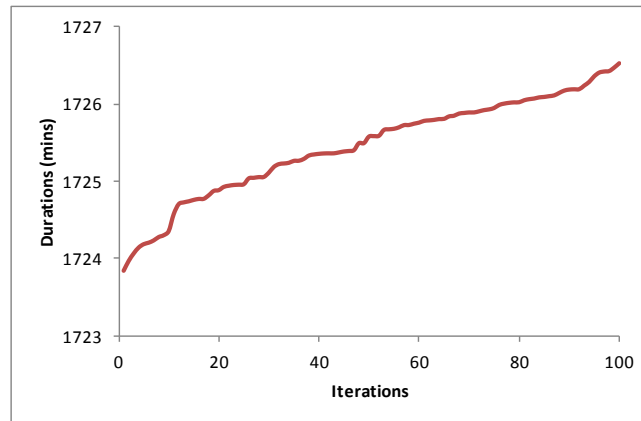


Figure 6: The sorted durations for the discussed model executed over 100 runs in SimFC's Earth-Sim.

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AUTHOR BIOGRAPHIES

JAMAL SIADAT is a PHD candidate in the Department of Civil Engineering, Project Management Specialization at the University of Calgary. With a background in software engineering and simulation, Jamal's main research objectives are to improve the overall simulation experience for all users. His e-mail is sjasiada@ucalgary.ca.

JANAKA Y. RUWANPURA is the Vice Provost (International) at the University of Calgary. He was a Professor and Canada Research Chair (CRC) in Project Management from 2007 to 2013, and the Founding Director of the Centre for Project Management (PM) Excellence at the University of Calgary. He has a diverse research portfolio including simulation, risk management and productivity studies. His collaboration with the industry has resulted in the identification of the top ten factors for improving construction productivity. This ground breaking work is an ongoing area of research with many potential benefits to the industry as a whole. Dr. Ruwanpura's e-mail is janaka@ucalgary.ca.