PREDICTING EQUIPMENT AVAILABILITY USING A HIGH LEVEL ARCHITECTURE FRAMEWORK

Estacio Siemann Santos Pereira[(a)], Yasser Mohamed[(b)], Simaan AbouRizk[(c)]

[(a)]University of Alberta
[(b)]University of Alberta
[(c)]University of Alberta

[(a)]estacio@ualberta.ca, [(b)]yasser.mohamed@ualberta.ca, [(c)]abourizk@ualberta.ca

ABSTRACT
Breakdown and maintenance can affect equipment availability, generating delays and increasing the cost of a project. The purpose of this paper is to develop a simulation model to predict equipment availability in earthmoving operations using a High Level Architecture framework. Based on user information, the model can verify the influence of the temperature, quantity of crews, location of breakdown and overheating of the tires on the equipment availability. The user can also define different distributions for maintenance and breakdown intervals, according to the equipment type and model. Different scenarios were defined to verify the model, and the results demonstrated that it can be useful to help inexperienced engineers to verify the influence of several parameters on the equipment availability and provide accurate information to the decision maker.

Keywords: Equipment Availability, High Level Architecture, Earthmoving

1. INTRODUCTION

Earthmoving operations, which are used in projects such as dams, highways and mines, utilize heavy equipment to increase productivity and decrease costs. Earthmoving operations typically include: excavating, loading, hauling, unloading, compacting and grading.

Inter-dependent activities require continuous work of the equipment during the entire project, without interruption, for better progress, productivity, and profits (Lee 2010). The equipment should be designed to ensure its successful operation though the anticipated service life, but deterioration starts as soon as the project begins (Muchiri et al. 2013). A major hindrance to achieving optimum production rates in earthmoving operations is equipment unavailability caused by maintenance and breakdowns.

There is a conflict of interest between the productivity rate and the maintenance and breakdown of equipment. Managers usually use the optimum use of equipment to create the project schedule. However, this approach does not consider the maintenance time. Lack of maintenance can increase the quantity of breakdowns. Companies should be able to develop maintenance management strategies to decrease the costs associated with unexpected problems with the equipment, define the optimum quantity of crews to fix broken equipment and define strategies to optimize the maintenance and breakdown intervals (Mohideen and Ramachandran 2014). An optimum scenario between maintenance, breakdown and equipment availability should be achieved in the project to avoid delays.

However, the equipment availability in these operations is generally affected by conditions that may give rise to uncertainty. Contractors should be able to predict these uncertainties to estimate the time and cost of projects, monitor the equipment availability, and make adjustments in response to the actual production performance to achieve a successful project (Mohideen et al. 2011).

According to AbouRizk (2010), when a problem is characterized by uncertainties, “simulation is the most suitable analytical tool to model and analyze the problems at hand.” In earthmoving operations, simulation models can be used to predict equipment availability, developing scenarios that help the decision maker improve the process (Moselhi and Alshibani 2010). However, due to the complexity of the operation, High Level Architecture (HLA) should be used to increase the accuracy of the simulation.

The purpose of this paper is to propose a simulation tool to allow testing different scenarios to better predict equipment availability in an earthmoving operation using an HLA framework.

2. EQUIPMENT MAINTENANCE AND BREAKDOWN

Maintenance is defined as a combination of technical and administrative activities required to keep equipment operating in its desired condition (BSI 1984). The main purpose of maintenance is to restore or improve equipment condition to keep it productive, in safe condition, and prolong its working life (Edwards and Holt 2009). According to Muchiri et al. (2013), there are three basic types of maintenance: failure-based maintenance—if the maintenance occurs just when the equipment fails; time-based maintenance—or periodic maintenance (PM), which is carried out at specified time intervals, but, failure can still occur between the intervals of PM; condition-based maintenance (CBM)—done when the PM is carried out whenever a given system parameter or condition reaches a predetermined value.

If well-established maintenance management is achieved, the company will have higher accuracy in predicting equipment breakdown, avoiding extra costs and being able to produce more reliable project schedules (Mohideen and Ramachandran 2014). Muchiri et al. (2013) concluded that different maintenance policies can lead to different equipment performances and that CBM policies provide better results when the interval time between the PMs is small. According to Edwards et al. (2000), the maintenance costs of an excavator in an opencast mine can represent up to 40% of production costs. However, lack of maintenance can result in project delays, loss of client goodwill, and reduced profit margins (Edwards and Holt 2009; Mohideen et al. 2011).

Another aspect to consider during maintenance is the crews' ability to take efficient action to fix the equipment. According to Muchiri et al. (2013), there are two extreme assumptions on the post-maintenance state of equipment: as good as new (AGAN) or as bad as old (ABAO). Periodic maintenance can reduce the equipment interval failure, but may not leave the equipment as good as new. Also, the equipment type and age affect the cost and time interval between the PMs. Competent plant operators can decrease the maintenance costs, because they can improve health and safety performance on the site and protect the equipment life-time by following the procedures recommended by the manufacturers (Edwards and Holt 2009).

Despite all the advances in maintenance management, equipment breakdown is inevitable. Breakdown can be defined as "the deterioration beyond the threshold level, decreasing the equipment performance in a critical level or loss of function of system performance" (Muchiri et al. 2013). The breakdown of equipment occurs due to the unpredictable failure of components and due to gradual wear and tear of the parts (Mohideen and Ramachandran 2014). Planners and estimators should account for potential lost time during the earthmoving operation, according to Harris and Olomolaiye (1993). Bernold (1989) mentions that breakdown is a well-known phenomenon and the random occurrence of such an event and duration to repair the equipment makes simulation a very efficient tool to analyze its impact. Some examples of random occurrences that affect breakdown are: equipment failure, tire problems (Mohideen et al. 2011), unexpected site conditions (Marzouk and Moselhi 2004), design limits, operational errors (Muchiri et al. 2013), lack (or quality) of maintenance (Snaddon 1988), type of truck, and hours of work (Wakefield and Sears 1997). Mohidden et al. (2011) identify the main causes for earthmoving equipment breakdown as mechanical failure, hydraulic failure and tire burst.

Zakeri et al. (1996) ranked equipment breakdown as the third most common cause of loss of productivity in construction. According to Nepal and Park (2004), breakdown represents an average of 6% of planned working time for equipment (specific percentages: crushers (19.3%), motor graders (9.9%), and trucks (8.6%)). Breakdown can affect not only the cost and production, but also the safety, behavior of the workers and team environment (Mohideen et al. 2011).

Some researchers have tried to establish connections between the factors that cause breakdown. Harris and Olomolaiye (1993) developed charts that relate the age of the equipment with the probability of breakdown; Elazouni and Basha (1996) correlated the usage and downtime of a piece of equipment due to breakdown; Wakefield and Sears (1997) developed a theoretical simulation model where the probability of breakdown is related to the equipment model.

Based on the literature review, an influence diagram was built to verify the main factors that can contribute to equipment breakdown (Figure 1). The four main factors that influence breakdown are maintenance, work hours, operational errors and equipment type. Although the main factors that contribute to breakdowns are known, there is need for a more detailed observation of the relationships between them. Due to this, some assumptions are made when forecasting the equipment breakdown because of the difficulties to measure factors such as operator skill and the influence of project characteristics on the equipment. The main interest in modeling breakdown occurrences is to analyze their effects on equipment availability and performance. In this research, we assumed that equipment deterioration and failure are factors of equipment utilization, and thus related to operation time.

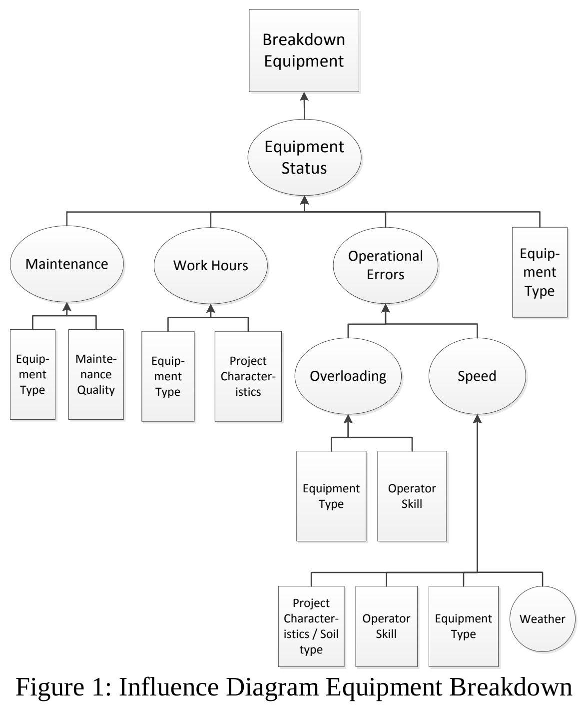


Figure 1: Influence Diagram Equipment Breakdown

3. METHODOLOGY

As there are many factors that can affect earthmoving operations, High Level Architecture (HLA) was used to simulate the maintenance and breakdown of equipment. High Level Architecture supports building complex virtual environments (called federations) using distributed computer simulation systems, to create a collaborative research project. In addition, it provides standards (composed by three main components: Rules (IEEE 1516), interface specifications (IEEE 1516.1) and the Object Model Template (IEEE 1516.2), that allow different developers to build their individual components (called federates) and exchange information between them (AbouRizk et al. 2009).

As the HLA is not software, the use of a run-time infrastructure (RTI) software is required to support the operations of a federation execution. The RTI provides services such as synchronization, communication, and data exchange between federates to support an HLA-compliant simulation. For this research, COSYE (AbouRizk et al. 2008) was utilized.

The breakdown and maintenance equipment federate (BMEF) is one of the current federates in this collaborative environment (federation) that receives and sends information through COSYE. To receive updates of an attribute, the federate should subscribe for this attribute, and to send an update, the federate should be able to publish to this attribute. In addition, another four federates also participate in the federation (Controller, Weather, Mover and Dumper). Figure 2 shows a schema of the federates' interaction with the federation. The simulation time is controlled by the RTI and the time step should be the same for all the federates.

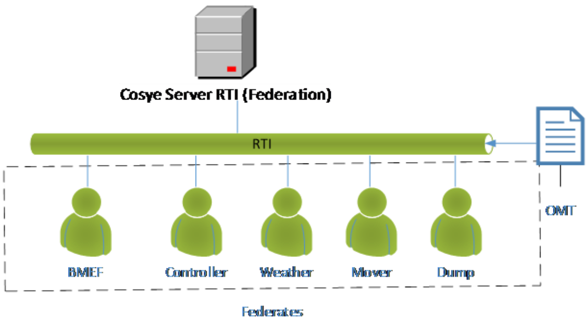


Figure 2: COSYE with Modeling Federates

The Object Model Template (OMT) contains the Federation Object Model (FOM), which contains all the objects, attributes and interactions for the federation, and the Simulation Object Model (SOM), which describes the object, attributes and interactions that a federate will use. If a federate wants to publish or subscribe to any attributes, it should be in the FOM and SOM. Figure 3 presents a conceptual model for the whole federation.

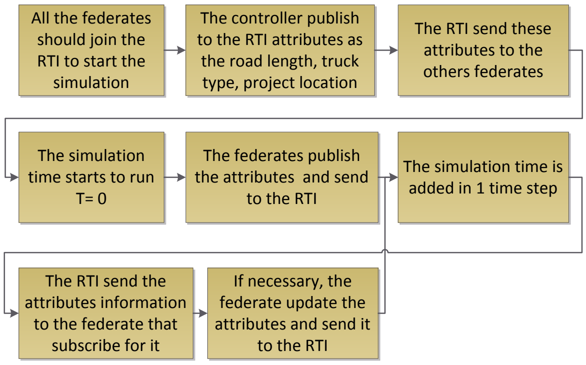


Figure 3: RTI Conceptual Model Process

At the beginning, all federates should join the RTI. The controller federate publishes the project location and start date, the road segments, the quantity of trucks and their characteristics, and the quantity of excavators and theirs characteristics. The other federates receive the information through the RTI and the controller federate allows the time to advance to start the simulation. In each time step, the RTI will send the attributes that were published from each federate to the federate that subscribes to that specific attribute. Also, the federates can publish new attribute values and send them to the RTI.

Each federate's function and interaction with the BMEF is described below:

- Controller Federate: The Controller Federate is an interface that regulates the simulation process and allows the user to update the project characteristics. The BMEF subscribes to the following attributes from this federate: truck model, quantity of each truck model, truck weight when empty, tire's Tons Kilometers Per Hour (TKPH) limit, excavator model and quantity of excavators. The Controller Federate subscribes to three attributes that the BMEF publishes: available equipment time, unavailable equipment time, equipment status and number of times that a truck reached the TKPH limit. With these attributes, the controller federate outputs graphs to the user that allow for easy understanding of the equipment availability. Figure 4 shows the interface where the user can update the project attributes and the truck availability outputs.

  The Controller Federate is also responsible for providing a graphic visualization of the truck location during the simulation run. If the truck is working, it is represented by the color green. If the truck needs service, the truck is represented by the color yellow and if it is down, it is represented by the color red (Figure 5).

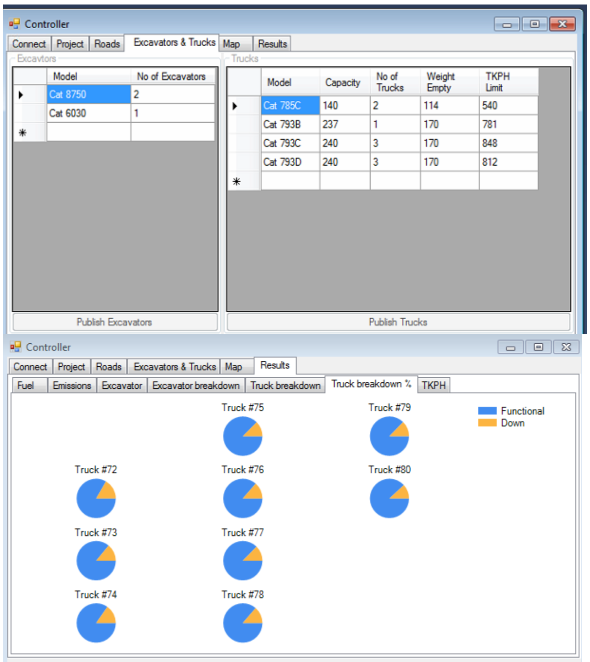


Figure 4: Controller Interface to Update the Truck and Excavator Initial Attributes and the Truck Availability Outputs

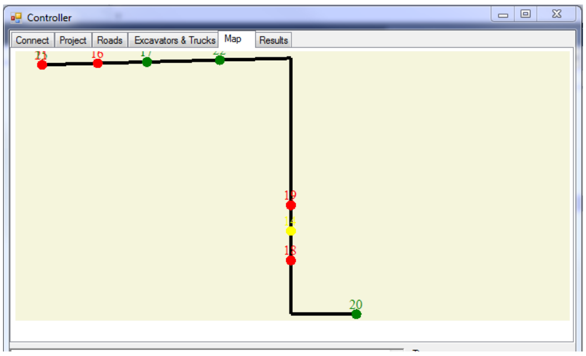


Figure 5: Controller Interface Showing the Truck Location and Status during the Simulation

- Weather Federate: This federate is responsible for publishing the weather conditions for the project location. The BMEF subscribes to all the parameters from this interaction class. Figure 6 shows the BMEF receiving an interaction with the weather parameters (89—Snow Fall; 90—Precipitation; 91—Visibility; 92—Wind Speed; 93—Temperature) during the simulation.

```
TKPH company 848.0
Requesting Time Advance to: 61.0
interaction received
[{89: 0.0, 90: 0.0, 91: 16.0, 92: 3.6, 93: 12.0}]
```

Figure 6: BMEF Receiving

- Mover Federate: This federate is responsible for moving the trucks in the project between the loading and unloading points. The BMEF subscribes to the Truck Location attribute and the Mover Federate subscribes to the truck Equipment Status. Figure 7 shows the BMEF receiving the Truck Location attribute during the simulation.

```
C:\Python33\python.exe
Truck 18
At time: 359.0 Attribute updated is received for object #19
0
Attr:21 = {'Z': 0.0, 'Y': 0.8104446507469563, 'X': 1.95}
Truck 19
At time: 359.0 Attribute updated is received for object #20
0
Attr:21 = {'Z': 0.0, 'Y': 1.225, 'X': 2.2}
Truck 20
At time: 359.0 Attribute updated is received for object #21
0
Attr:21 = {'Z': 0.0, 'Y': 0.275, 'X': 1.0}
Truck 21
At time: 359.0 Attribute updated is received for object #22
0
Attr:21 = {'Z': 0.0, 'Y': 0.25714095250822794, 'X': 1.678643
Truck 22
At time: 359.0 Attribute updated is received for object #14
0
Attr:21 = {'Z': 0.0, 'Y': 0.9080921047590471, 'X': 1.95}
Truck 14
At time: 359.0 Attribute updated is received for object #15
0
Attr:21 = {'Z': 0.0, 'Y': 0.275, 'X': 1.0}
Truck 15
```

Figure 7: BMEF Subscribes to the Truck Location Attributes from the Mover Federate

- Dumper Federate: This federate is responsible for loading and unloading the trucks. The BMEF subscribes to the Truck Load State and Payload and the Dumper Federate subscribes to the Excavator Equipment Status. Figure 8 shows the BMF receiving the Truck Load State attribute (Attr:35) from the Dumper Federate through the RTI.

```
22
Total distance 12.3720113117
tkph_per_tyres 595.624884198
TKPH company 812.0
Requesting Time Advance to: 357.0
At time: 356.4318066221646 Attribute updated is received for object #22
e stamp 356.4318066221646
Attr:33 = 240.0
Attr:35 = LoadStates.Loaded
At time: 357.0 Attribute updated is received for object #17 with time st
0
```

Figure 8: BMEF Subscribes to the Truck Load State Attributes from the Dumper Federate

Other interactions happen between the other federates, but they do not affect the BMEF and are not part of this research's scope.

3.1. BMEF Algorithm and Characteristics

The BMEF is responsible for calculating the equipment availability and publishing the equipment states as Functional, Down or Need Service. The federate works in a condition-based maintenance way. Aside from the information provided by the Controller Federate, the user should fill the data_breakdown.csv file (Figure 9) with the information requested. As the main data required are distributions, the federate supports the following types: Normal, Uniform, Triangular, Exponential, Constant and Beta. The file also accepts values between 0 and 1. In this case, the user should update the distribution type with the word "Float." The parameter columns (P1 to P5) are the parameters necessary for each type of distribution. As an example, a uniform distribution with a low value of 5 and maximum of 10 should be updated in the model as follows: Distribution: uniform; P1 = 5; and P2 = 10.

Description	Distribution	P1	P2	P3	P4	P5
Cat 785C breakdown						
Cat 793B breakdown						
Cat 793C breakdown						
Cat 793D breakdown						
Time to repair						
Increase time field						
Cat 785C maintenance						
Cat 793B maintenance						
Cat 793C maintenance						
Cat 793D maintenance						
Time to maintenance						
Probability truck break on Field						
Increase time repair temperature < -30						
Crews available						
Cat 8750 breakdown						
Cat 6030 breakdown						
Time to repair Excavator						
Cat 8750 maintenance						
Cat 6030 maintenance						
Time to maintenance Excavator						

Figure 9: CSV File for Input Data

In Figure 4 it can be observed that the model lets the user define more than one model of truck and excavator. The *Time to repair* is the total time for the truck to be repaired after breakdown. In this federate, two types of truck breakdowns are considered: in the field or in the shop. The user should define the probability (value between 0% and 100%) of a truck breaking down in the field in the row *Probability truck breakdown in the field*. If the truck breaks down in the field, the user can increase the repair time in the row *Increase time field* (between 0% and 100%). The repair time can also be increased (between 0% and 100%) if the temperature is less than -30ºC in the row *Increase time to repair temperature is less than -30 ºC*. The *Time to Maintenance* will be the same for all truck models.

The excavators will always break down in the field, and the *Time to repair* excavator will also be increased if the temperature is less than -30ºC. The *Maintenance Time* is the same for all the excavators. The user can also specify the quantity of crews available for equipment repair and maintenance. Figure 10 demonstrates the algorithm used in the BMEF to calculate the breakdown and maintenance intervals for the truck equipment.

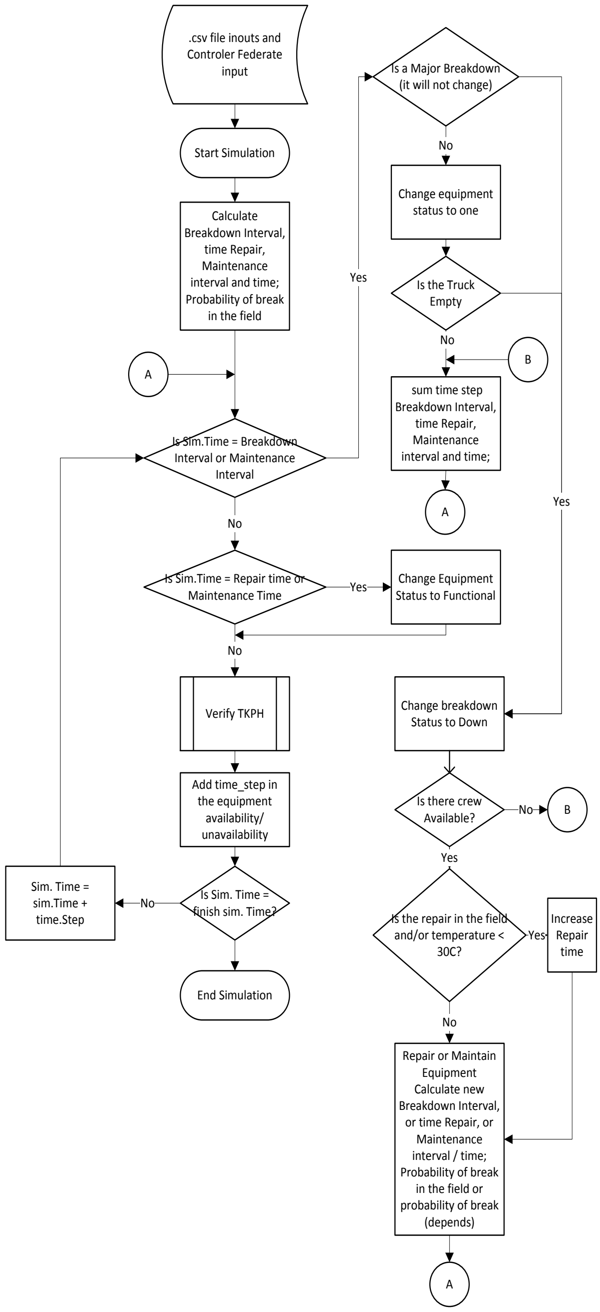


Figure 10: Algorithm Used in the BMEF for the Truck

With the users' inputs from the Controller Federate and the breakdown.csv file, the simulation starts. When the simulation time = 1, the truck (object) should define the following values: the next *Breakdown and Maintenance Interval*; *Time to repair* the equipment; *Time to maintain* the equipment; and a random number between 0 and 1 is generated to compare with the *Probability of breaking in the field*. The BMEF should receive the parameters that it subscribes to in every time step. The simulation time should be increased by one time step. If a truck breaks and it is a minor breakdown or if it is maintenance time, it should be emptied to be repaired or maintained. If the truck is empty or the breakdown is a major breakdown, the breakdown state will change to down and this information is published. If there is a crew available, the truck can be fixed. After repairing or maintaining the truck, a new interval for breakdown or maintenance should be calculated. Other characteristics of the BMEF are described below:

- If a truck needs to wait to be emptied for repair or maintenance, or if equipment needs to wait for a crew, the *Time to repair* and *Maintenance interval* should be increased by the total waiting time for these resources to avoid the two events from happening at the same time.
- If a piece of equipment is in maintenance, the *Breakdown Interval* should be added with this time as the distributions for breakdown and interval only consider working hours. The same procedure should be performed when the truck is repaired. In this case, the *Maintenance Interval* should be increased by the repair time.
- For each piece of equipment in every time step, the federate verifies the equipment status. If the *Breakdown State* is *Functional* or *Need Service*, the *Available Time* should be increased by the time step, and if the *Breakdown State* is *Down*, the *Unavailable Time* is increased by the time step.

The BMEF also verifies if a truck is exceeding the TKPH limit provided by the user. The TKPH is a measurement of the work load of a tire and is based on the weight and distance (or speed) that the tire can travel without overheating. If the TKPH maximum value is achieved, the truck should stop for 60 minutes to decrease the tire temperature. It is assumed that all the truck tires have the same workload. The TKPH is calculated using Equation 1:

$$TKPH = \sum_{i=1}^{60}\left(\frac{(TEW+P_{(i)})}{6} * \left(TTD_{(i)} - TTD_{(i-1)}\right)\right) \quad (1)$$

Where:

- TEW: Truck Empty Weight (tons)
- P: Payload—the amount of material carried by the truck at a specific time (tons)
- TTD - Total Truck Distance—distance traveled by the truck in 1 minute (km)

Figure 11 shows the algorithm used to verify if the truck achieved the TKPH limit defined by the user. Figure 12 shows the calculation executed by the BMEF for each truck (19,20,21), comparing the TKPH calculated and the TKPH provided by the user in the Controller Federate.

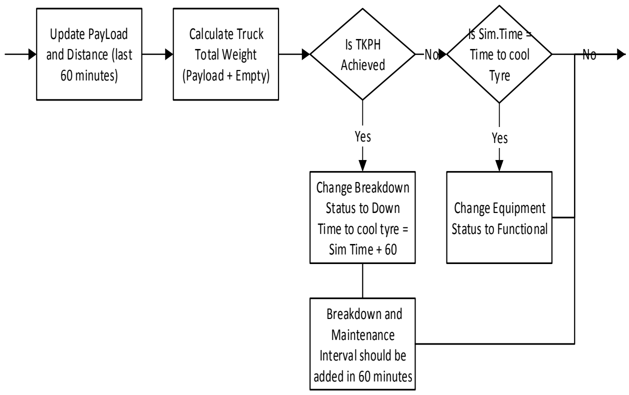


Figure 11: TKPH Algorithm

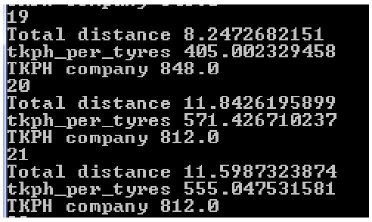


Figure 12: TKPH Calculated per Tire in the BMEF

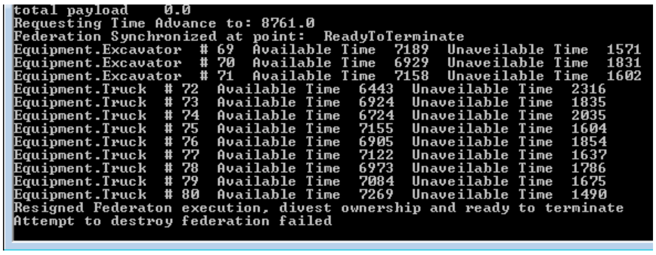
4. SCENARIOS AND RESULTS

To verify the BMEF behavior, two scenarios were tested. In the first scenario, the TKPH limit was not considered, and the parameters used in the simulations were retrieved from empirical data. They were used as input data for the simulation. The weather parameters used in scenario 1 were defined by the Weather Federate and they are from Fort McMurray (Alberta, Canada). The parameters used are described in Table 1. Several combinations were developed to demonstrate the options that the user can test with the BMEF. Only the Weather, Controller and BMEF federates were used in this scenario, and the time step is defined in hours.

Seven combinations were developed with the parameters defined in Table 1. After testing each combination, the BMEF provides the availability for each piece of equipment (Figure 13). The combinations vary in the number of crews, probability of breakdown in the field and weather parameters (Table 2). The total simulation time is 8760 hours (one year) and the equipment runs in 24/7 shifts.

Table 1: Parameters Used in Scenario 1

Parameters	**Duration (h) / Specification**
Truck Breakdown Interval (same for all truck models)	Exponential (200)
Truck Maintenance Interval (same for all the trucks)	Constant (400)
Time to Repair Truck	Uniform (20, 24)
Time to Maintenance Truck	Triangular (18,21,24)
Increase Time to Repair in the Filed	10%
Increase Time Repair Temperature is less than -30ºC	20%
Excavator Breakdown Interval (same for all excavator models)	Exponential (250)
Excavator Maintenance Interval (same for all the excavators)	Constant (350)
Time to Repair Excavator	Uniform (20, 24)
Time to Maintenance Excavator	Triangular (18,22,25)
Quantity of Trucks	9
Quantity of Excavators	3



```
total payload    0.0
Requesting Time Advance to: 8761.0
Federation Synchronized at point:  ReadyToTerminate
Equipment.Excavator  # 69  Available Time  7189  Unaveilable Time  1571
Equipment.Excavator  # 70  Available Time  6929  Unaveilable Time  1831
Equipment.Excavator  # 71  Available Time  7158  Unaveilable Time  1602
Equipment.Truck  # 72  Available Time  6443  Unaveilable Time  2316
Equipment.Truck  # 73  Available Time  6924  Unaveilable Time  1835
Equipment.Truck  # 74  Available Time  6724  Unaveilable Time  2035
Equipment.Truck  # 75  Available Time  7155  Unaveilable Time  1604
Equipment.Truck  # 76  Available Time  6905  Unaveilable Time  1854
Equipment.Truck  # 77  Available Time  7122  Unaveilable Time  1637
Equipment.Truck  # 78  Available Time  6973  Unaveilable Time  1786
Equipment.Truck  # 79  Available Time  7084  Unaveilable Time  1675
Equipment.Truck  # 80  Available Time  7269  Unaveilable Time  1490
Resigned Federaton execution, divest ownership and ready to terminate
Attempt to destroy federation failed
```

Figure 13: Output Availability/Unavailability of Each Piece of Equipment in the BMEF

Table 2: Different Combinations in Scenario 1

Com -bo	**Crew**	**Prob. Break-down in field**	**Wea-ther para-meters**	**Trucks unavail -able (%) (min, mean , max)**	**Excav-ators unava-ilable (%) (min, mean , max)**
1	2	50%	N	(17, 21, 26)	(18 ,19, 21)
2	4	50%	N	(13, 15, 16)	(13, 14, 15)
3	4	100%	N	(73, 77, 78)	(76, 77, 77)
4	4	75%	N	(13, 14, 15)	(14, 15, 17)
5	6	100%	N	(12, 14, 15)	(14, 14, 15)
6*	4	50%	N	(14, 15, 15)	(13, 14, 15)
7	4	50%	Y	(12, 14, 15)	(13, 16, 18)

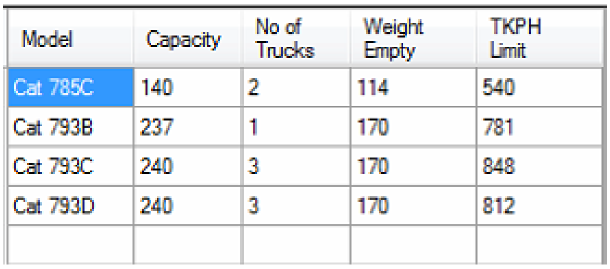
* Combination 6 used *Constant Distribution* (200h) for *Truck and Excavator Breakdown Interval*.

It is possible to see that between combination 1 and 2, the truck and excavator unavailable times were decreased by 29% (comparing the mean) just by changing the quantity of crews. The unavailability of the trucks between combinations 2 and 3 increased 400% with a change in the probability breakdown in the field. This was expected, because the quantity of crews (4) is not enough if the repair time increases. In the same way, if the crew number increases to 6 (combination 5), the trucks' unavailability time is almost the same, when compared with combinations 2 and 4.

Combination 6 has constant distribution for breakdown interval (200h), but the equipment unavailable time was not increased. This result can be explained because the crew availability will be limited for the first breakdown, but not for the subsequent events, as the following breakdowns will happen at different times. However, the effect of the constant interval time on the cycle time should be investigated.

Combination 7 was the only one to consider the temperature to fix the equipment in the field, and the difference between this combination and combination 2 was not significant. The BMEF will be more influenced by the temperature if the probability of breakdown in the field is also increased. Moreover, the weather will not always affect equipment repair time, since the temperature changes every hour, and the mean temperature in Fort McMurray is higher than -30 ºC.

In the second scenario, the TKPH limit was considered. The truck speed limit (50 km/h) and tire TKPH is defined by the user in the Mover and Controller federates, respectively, and the BMEF has no control on these parameters, thus limiting the combinations used in this scenario. The parameters used by the Controller Federate are described in Figure 14. In this scenario, only the Weather Federate was not used and the time step is defined in minutes.



Model	Capacity	No of Trucks	Weight Empty	TKPH Limit
Cat 785C	140	2	114	540
Cat 793B	237	1	170	781
Cat 793C	240	3	170	848
Cat 793D	240	3	170	812

Figure 14: Trucks Parameters to Verify the TKPH Limit (Defined in the Controller Federate)

The distribution for the breakdown in scenario 2 was changed to verify the influence on the truck unavailability. The breakdown interval and time to repair are the same for all the truck models and it was based on the assumptions made by Chang et al. (2013)

(Table 3). The simulation total time is 10,080 minutes (one week).

Table 3: Parameters Used in Scenario 2

Parameters	Duration (min)/ Specification
Truck Breakdown Interval (same for all truck Types)	Triangular (300, 360, 480)
Time to Repair Truck	Triangular (60,80, 150)
Increase Time to repair in the filed	10%
Quantity of Trucks	9
Maintenance Interval	Constant (1000)
Maintenance Repair	Triangular (60,80,150)
Probability of Breakdown in the Field	50%
Quantity of crews	4

The results show that the trucks achieved the TKPH limit between 50 and 42 times during the simulation and the mean unavailable time for the trucks is 57% (Figure 15). It is possible to observe that the BMEF was able to verify the TKPH limit and this value cannot be disregarded during the planning phase. Suggestions to increase the available time are: increase the tire TKPH, decrease the truck speed limit, or if possible, decrease the cycle time.

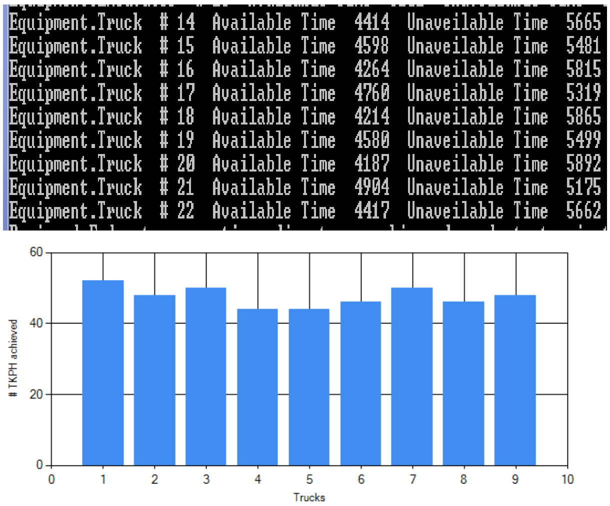


Figure 15: Truck Available and Unavailable Time (Provided by the BMEF) and Quantity that Each Truck Achieved the TKPH Limit (Provided by the Controller Federate)

5. VERIFICATION AND VALIDATION

The model output was examined under a variety of settings to perform model verification. Based on the scenarios and combinations developed, the BMEF demonstrated logic, and it is possible to verify that the model was implemented properly. The development of the simulation model made it possible to verify the influence of different parameters on equipment availability (as shown in the scenarios 1 and 2 in Section 4). The BMEF demonstrated the effect of the quantity of crews, weather parameters, TKPH limits and the probability of the equipment breakdown in the field, as well as the type of distribution for maintenance and breakdown (Figure 13 and 15). The model behavior was also verified through the Controller Federate showing the equipment breakdown status. Also, the outputs provided by the BMEF and the Controller Federate are coherent.

However, as the data used to verify the BMEF was empirical, further research should be performed to validate the model. It is suggested that real data be used to verify the BMEF behavior, and necessary adjustments be done to increase the simulation model accuracy. Another possible way to validate the federate is through a face validation.

6. CONCLUSION

The research objective was achieved. The simulation model developed was able to verify the influence of different parameters on the equipment availability in an earthmoving operation and help the decision makers with maintenance management. The results can be used to improve the project schedule and engineers with limited experience can use the simulation model to verify the influence of the parameters on the equipment availability. The BMEF was able to receive data from other federates through the RTI and increase the model accuracy results.

To improve the model results, as indicated, actual data should be used in order to produce real results. The increment of time repair as a consequence of the temperature and localization (shop or field) needs further research. The relationship between maintenance and breakdown intervals should also be studied in greater depth, as it is agreed that shorter maintenance intervals can decrease breakdown occurrences. As an improvement, we should consider adding to the model the tire usage cycle, and the maintenance and breakdown intervals can be divided in different causes to provide a more realistic environment.

ACKNOWLEDGEMENT

This research was made possible in part by Coordination for the Improvement of Higher Education Personnel (CAPES) Ministry of Education of Brazil (Proc. n° 0393-12-6).

REFERENCES

Abourizk, S. (2010). Role of Simulation in Construction Engineering and Management. Journal of Computing in Civil Engineering, 136, 1140–1153.

AbouRizk, S. M., Hague, S., and Moghani, E. (2009). Developing a Bidding Game Using High Level Architecture. In Computing in Civil Engineering (2009) (513–522). Reston, VA: American Society of Civil Engineers. doi:10.1061/41052(346)51

AbouRizk S. M., Robinson Fayek, A. (2008). “Synthetic Environments for Construction Planning

and Control." NSERC IRC Renewal application 2007-2011, pp. 11-15
Bernold, L. (1989). Simulation of Nonsteady Construction Process. Journal of Construction Engineering and Management, 115(2), 163–178.
BSI. 1984. Glossary of Maintenance Terms in Terotechnology. London: British Standard Institution (BSI), BS 3811
Chi, S., and Caldas, C. H. (2009). Development of an Automated Safety Assessment Framework for Construction Activities. In IAARC (Ed.), Proceedings of 26th International Symposium on Automation and Robotics in Construction (ISARC) (pp. 38–46). Austin, TX.
Edwards, D. J., and Holt, G. D. (2009). Construction plant and equipment management research: thematic review. Journal of Engineering, Design and Technology, 7(2), 186–206. doi:10.1108/17260530910974989
Elazouni, A. M., and Basha, I. M. (1996). Evaluating the Performance of Construction Equipment Operators in Egypt. Journal of Construction Engineering and Management, 122, 109–114.
Harris, F. C., and Olomolaiye, P. O. (1993). A theoretical model for determining equipment service life. Building Research and Information, 21(4), 243–245. doi:10.1080/09613219308727305
Lee, T.-Y. (2010). Development and Validation of Rolling Resistance-Based Haul Road Management For. Purdue University.
Marzouk, M., and Moselhi, O. (2004). Multiobjective Optimization of Earthmoving Operations. Journal of Construction Engineering and Management, 130, 105–113.
Mccann, M. (2006). Heavy equipment and truck-related deaths on excavation work sites. Journal of Safety Research, 37, 511–517. doi:10.1016/j.jsr.2006.08.005
Mohideen, P. B. A., and Ramachandran, M. (2014). Strategic approach to breakdown maintenance on construction plant – UAE perspective. Benchmarking: An International Journal, 21(2), 226–252. doi:10.1108/BIJ-05-2012-0030
Mohideen, P. B. A., Ramachandran, M., and Narasimmalu, R. R. (2011). Construction plant breakdown criticality analysis – part 1:UAE perspective. Benchmarking: An International Journal, 18(4), 472–489. doi:10.1108/14635771111147597
Moselhi, O., and Alshibani, A. (2010). Optimization of Earthmoving Operations in Heavy Civil Engineering Projects. Journal of Construction Engineering and Management, 135(10), 948–954.
Muchiri, P. N., Pintelon, L., Martin, H., and Chemweno, P. (2013). Modelling maintenance effects on manufacturing equipment performance: results from simulation analysis. International Journal of Production Research, 1–16. doi:10.1080/00207543.2013.870673
Nepal, M. P., and Park, M. (2004). Downtime model development for construction equipment management. Engineering, Construction and Architectural Management, 11(3), 199–210. doi:10.1108/09699980410535804
Snaddon, D. (1988). Breakdown Theories and Complex Units A Critique. Omega International Journal Of Management, 16(2), 135–143.
Wakefield, R. R., and Sears, G. A. (1997). PETRI Nets for Simulation and Modeling of Construction Systems. Journal of Construction Engineering and Management, 123, 105–112.
Zakeri, M., Olomolaiye, P., Holt, G., and Harris, F. (1996). A survey of constraints on Iranian construction operatives' productivity. Construction Management and Economics, 14(5), 417–425.