Optimising Shovel-Truck Fuel Consumption using Stochastic Simulation*

[1]N. K. Dumakor-Dupey, [1]V. A. Temeng and [2]K. J. Bansah
[1]University of Mines and Technology, P. O. Box 237, Tarkwa, Ghana
[2]Missouri S&T, Rolla-Missouri, USA

Dumakor-Dupey, N. K., Temeng, V. A. and Bansah, K. J. (2017), "Optimising Shovel-Truck Fuel Consumption using Stochastic Simulation", *Ghana Mining Journal,* Vol. 17, No. 2, pp. 39 - 49.

Abstract

Stochastic simulation was conducted to analyse the fuel consumption of a shovel-truck system. An example shovel-truck system, comprising a single shovel and four trucks was considered. At 95% confidence interval, the monthly simulated fuel consumption by the shovel-truck system was found to be about 198 127 litres against the actual fuel consumption of 203 772 litres, registering a variance of -2.70%. About 22 000 litres of fuel was consumed per month due to truck waiting. Optimising the fuel consumption and truck waiting time can result in significant fuel savings. The paper demonstrates that stochastic simulation is an effective tool for optimising the utilisation of fossil-based fuels in mining and related industries.

Keywords: Stochastic, Simulation Modelling, Mining, Optimisation, Shovel-Truck Material Handling

1 Introduction

The decline in gold price together with escalating cost of production has necessitated a more effective and efficient means of reducing overall mining cost. Materials handling cost is reported to be one of the main constituents of the high production cost in mining operations. Nel *et al.* (2011) report truck haulage as the largest operating cost centre in surface mining operations, constituting 50 – 60 percent of the total mining cost. Fuel consumption has always been one of the primary operating costs associated with shovel-truck operations, with fuel cost representing a significant component of materials handling cost.

Fuel consumption has been a core consideration since the beginning of mining due to economic and environmental concerns. The mining industry has traditionally relied on conventional fossil-based fuel sources such as diesel and natural gas to meet its growing energy demand. This reliance on diesel fuel for operations in mining continues to affect the total cost of operations. Additionally, the combustion of diesel fuel contributes to greenhouse effect through the release of carbon dioxide (CO_2). According to Adak *et al.* (2016), Norgate and Haque (2010), Kecojevic and Komljenovic (2010), materials handling makes the largest contribution to the total greenhouse gas emissions compared to other principal mining operations. Hence, efficient fuel usage in materials handling can contribute immensely to reduction in greenhouse emissions.

According to Kecojevic and Komljenovic (2010), there are two ways of determining fuel consumption of trucks: using data from actual mine operations and or utilising various equations and data provided by the truck Original Equipment Manufacturer (OEM). They further determined the hourly fuel consumption using Equation 1. Values for the truck engine Load Factors (LF) range from 0.18 to 0.75, depending on the equipment type and level of use.

$$FC = 0.3 \times P \times LF \tag{1}$$

where

FC = Fuel Consumption (L/hr);
P = engine power (kW);
0.3 = unit conversion factor (L/kW/hr);
LF = engine load factor (the portion of full power required by the truck).

Parreira (2013) improved Equation 1 by introducing Specific Fuel Consumption (SFC) and fuel density as follows (Equation 2):

$$FC = (SFC \times P \times LF)/FD \tag{2}$$

where

SFC = Specific Fuel Consumption (0.213 – 0.268 kg/kW/hr);
P = engine power (kW);
LF = engine Load Factor;
FD = Fuel Density (0.85 kg/l for diesel).

Lin *et al.* (2011) summarised the factors that influence vehicle's fuel economy into four main categories, namely, vehicle performance, road traffic situation, environmental condition, and driver operating behaviour. Awuah-Offei *et al.* (2012) provides three main factors affecting fuel consumption as operator practices, operating conditions, and equipment. Thus, fuel consumption does not only occur as a result of the vehicle's design, manufacturing, and assembly, but also, road condition and driver's behaviour. Heide and Mohazzabi (2013) in their concept of parallel

*Manuscript received March 07, 2017
Revised version accepted November 29, 2017
https://dx.doi.org/10.4314/gm.v17i2.6

corridors experiment, demonstrated how airspeed affects fuel consumption even though acceleration and deceleration, gear changing, as well as the speed of the vehicle also have significant effect on fuel consumption.

Gold Fields Ghana Limited (GFGL), Tarkwa Mine, located in the Western Region of Ghana, faces high cost of materials handling due to increasing fuel consumption during loading and hauling of fragmented waste rock and ore. The mine (GFGL) adopts the shovel-truck system for loading and hauling operations. Several shovel-truck systems with varying number of trucks matched to a shovel are used at GFGL. In this study, one shovel-truck system (a single shovel matched with four trucks) was considered. Several mechanisms and technologies are being adopted to reduce and achieve efficient fuel consumption (Koellner *et al*., 2004). In this paper, a stochastic simulation model is developed with Arena simulation software to analyse the fuel consumption of the shovel-truck system at GFGL.

1.1 Mining Applications of Arena

Stochastic simulation model is widely used in the mining industry (Li *et al.,* 2004), especially in the area of risk analysis. Arena, a discrete event simulation software developed by Systems Modelling Corporation and acquired by Rockwell Automations (Altiok and Melamed, 2007) has been used in the mining industry for various applications, including modelling shovel-truck systems, underground mining activities, and metallurgical processes. Krause and Musingwini (2007) explained that Arena is a very flexible model for use in analysing several variables in shovel-truck systems due to its ability to be programmed with any number of probability distribution models fitted to an unlimited number of cycle variables. Thus, Arena has the potential to closely imitate real systems.

Fioroni *et al.* (2008) demonstrated how simulation and optimisation models can be combined with simultaneous execution to correctly analyse and generate short-term planning schedules to meet desired production target. The models were applied and approved at Vale's Aguas Claras Mines complex and were used for planning purposes. While the simulation models were developed in Arena and that of optimisation in Lingo, Visual Basic for Application (VBA) was used for communication between the simulator and the optimiser.

Awuah-Offei *et al.* (2012) used Arena to study energy efficiency of shovel-truck haulage system in a surface coal mine in the United States. A stochastic model representing the haulage operation was built with Arena and investigated the effects of using larger shovel and optimising shovel-truck matching for the purpose of fuel efficiency. The results showed that a larger shovel has positive correlation on fuel efficiency. Optimised shovel-truck matching did not reduce the fuel consumption rate.

In a research conducted by Shelswell *et al.* (2013), the conventional method for determining truck haulage fleet requirements for quarterly development-production schedule in an underground mine derived from Tonne-Kilometre (TKM) calculation was compared to discrete simulations with an Arena model. The estimated TKM truck fleet was found to have diverged from the truck fleet estimated by the Arena model. This is because historically-based TKM calculations do not adequately account for changing operational factors. The Arena model was also used to test the feasibility of alternate production-development schedules, predict resource utilization, and perform trade-off analyses on operating practices.

Koenig *et al.* (2002) developed a reliability model to confirm plant design capacity of Stanwell Magnesium Plant. The operation of the magnesium plant was modelled using Arena. The reliability model was established using the detailed process flow diagrams. The reliability model was used to evaluate surge capacities required between different sections of the plant, critical equipment requiring standby capacity, the number of trains required for different sections of the plant, and potential capital cost reduction options.

Arena has also been widely applied in other industrial applications, including health care (Jun *et al.,* 1999; Wang *et al.,* 2009; Komashie and Mousavi, 2005), agriculture (Hogg *et al.,* 2010), manufacturing (Rogers, 2002; Kumar and Phrommathed, 2006; Anglani *et al.,* 2002), supply chain (Patil *et al.,* 2011), cyber security (Kuhl *et al.,* 2007), shipping (Zeng and Yang, 2009).

1.2 Shovel-Truck System at GFGL

GFGL uses conventional rear dump off-highway trucks in conjunction with hydraulic excavators for loading and hauling of fragmented rocks. Mining at one of the pits- Underlap Cutback Pit, involves the use of two excavators (Liebherr 9250 and Liebherr 984) for digging and loading in 3 m lifts or 6 m lifts depending on the type of material being loaded. Each excavator is matched with a number of dump trucks which could be mixed fleets or same fleets. The Liebherr 9250, labelled as Ex 16 is matched with four CAT 785C trucks but it can also be matched with a mixed fleet *i.e.* CAT 785C and Komatsu 785 trucks.

This work considered only Ex 16 and four CAT 785C trucks. Loading and hauling is carried out 24 hours per day (12 hours per day shift and 12 hours per night shift). A 30-minute break and 30 minutes shift change durations are allowed for both shifts. Trucks are loaded at Ex 16 and haul the material to either the ROM pad or Cut-1 waste dump and then travel back to the shovel to be loaded again (Fig. 1). The process continues until it is break time when all trucks are parked in the pit near the Ex 16 for workers to go for lunch. The loading and hauling process resume after lunch, until the shift is over at 6:00 pm, when all trucks are parked at Short Body Park or in the pit. The night crew continue the routine until 6:00 am in the morning.

As the fuel gauges read 20% or below, during the course of operations, the trucks travel to the fuel farm for re-fuelling. The re-fuelling of the excavator is done in the pit by service vehicles.

2 Resources and Methods Used

2.1 Data Collection

Time and motion studies were conducted to determine the cycle time. The data sets obtained include:

(i) Loading time;
(ii) Hauling time;
(iii) Spotting and dumping time;
(iv) Travelling times;
(v) Fuelling time;
(vi) Fuel burning rate of Ex 16 and the four CAT 785C trucks; and
(vii) Fuel consumption data from December 2014 to January 2015.

Also, in order to develop a true model of the shovel-truck system of the mine, various activities of the shovels and trucks at the pits and dumps were observed carefully. Such activities include shovel digging and tramming, truck dumping, spotting and manoeuvring.

2.2 Data Analysis

Arena Input Analyzer was used to analyse the collected data to obtain histograms of the representative data, best fit distributions, and parameters and expressions. The parameters and expressions were thereafter used as input data for the Arena modules. Also, square errors for both theoretical distributions and hypothesized distributions were determined. It is noted that the smaller the square error, the better the hypothesized distribution and vice versa.

Chi-square and Kolmogorov-Smirnov goodness of fit tests were performed on the representative data at 5% significance level by the Input Analyzer. Table 1 is a summary of the input expressions and their corresponding square errors as well as their p-values for the various representative data.

Fig. 1 Layout of Underlap Cutback Pit

Table 1 Distributions and Parameter Estimates for Cyclic Activities of Trucks Assigned to Ex 16

Random Variable	Distribution	Expression (minutes)	Square Error	P-value α=5%
Loading Time	Triangular	TRIA(2.71, 4.25, 4.61)	0.017744	0.386
Hauling Time (Waste)	Beta	9 + 2.92 × BETA(1.06, 1.98)	0.037128	0.0853
Hauling Time (Ore)	Beta	3.66 + 2.28 × BETA(0.938, 1.33)	0.093822	0.0424
Dumping Time	User Defined	Continuous		
Travelling from Waste Dump Time	Triangular	TRIA(4.14, 5.98, 6)	0.010774	0.622
Travelling from Crusher Time	Beta	1.82 + 1.54 × BETA(1.33, 1.55)	0.008430	0.432
Waiting Time	Triangular	TRIA(2.71, 4.25, 4.61)	0.017744	0.386
Tonnage per Cycle	Triangular	TRIA(135, 142, 148)	0.096926	0.75
Travelling to Pit Park	User Defined	Continuous		
Travelling to Shortbody Park	User Defined	Continuous		
Travelling to Fuel Farm	User Defined	Continuous		

2.3 Shovel-Truck System Modelling

The analysis of fuel consumption at GFGL was based on a stochastic model of the shovel-truck system of the mine. The following variables were incorporated into the model: loading times, travelling (loaded) times, spotting and dumping times and travelling (empty) times of the trucks. Break times consisting of lunch, change of shifts and night breaks were also incorporated. A conceptual model (Fig. 2) that describes the various activities and stages of the shovel-truck system of the mine was developed before the final modelling.

The model of the shovel-truck system is process oriented; that is, truck entities with the help of a transporter module travel in a cyclic manner between shovel station and either waste dump station or crusher station depending on the material type. Also, the truck entities may travel from shovel station to the fuel farm station, the pit park station or the shortbody park station. Various modules in Arena were organised to develop the model that depict the major operations of the shovel-truck system. Fig. 2 illustrates Arena shovel-truck model of GFGL Underlap Cutback Pit.

2.3.1 Trucks Entity Creation

Four trucks assigned to Ex 16 were created at the beginning of the simulation, depicting the commencement of a shift. The model does not include inter-arrival time of truck since the mine shift schedule is such that trucks will be in the pit before the start of production by the next shift. Create module in the Arena template was used to create the trucks.

2.3.2 Shovel Process

The Process module was used to model the operation of the shovel such that the shovel seizes one truck, delays it for a random loading time, and releases it for the truck load to be recorded by the Record module before it proceeds to a dumping station or crusher station. Each load is approximately 145 tonnes. The Assign module changes the truck status to loaded truck and revert it after dumping.

2.3.3 Shovel and Truck Fuel Consumption Process

The modelled shovel and truck operations are such that the fuel consumed in the course of operation is recorded for both shovel and trucks. The fuel consumption is modelled as an attribute based burning rate per hour of the shovel (169 l/hr) and trucks (93 l/hr). The burning rates were inputs in the operand of the resource dataset and entity dataset.

The fuel farm is modelled as resource which is seized by the truck entities during fuelling at the beginning of the shift.

2.3.4 Truck Movement Process

Trucks were modelled to move from one station to another portraying the reality of trucks moving from a shovel to a dump or from a dump to a parking station and/or from a parking station to a shovel. The following practices and assumptions of the mine were applied to the modelled trucks processes:

(i) All trucks are similar in terms of their speeds.
(ii) The mine roads provide two-way-traffic for trucks.

The Route module was used to transfer the truck entities from one station to another at specified times. The travelling times both loaded and empty were inputs in the operand of the Route module. This transfer process depicts the travelling times from shovels to dumps and/or from dumps to shovels.

2.3.5 Dumping Process

The Process module was used to model the dumping process like the shovel process since the dumps also seize truck, delays it for a dumping time, and releases the truck to travel from the dumping station to a shovel or parking station depending on the time into a day's operation. The dumping times distributions were input in the delay time operand of the Process module.

2.3.2 Break Time Modelling

Lunch, shifts change and night meal times which were the operational breaks were modelled such that trucks were parked at a particular place after dumping their material a few minutes to break time, as practiced by the mine. The trucks were then batched and delayed for the break time to end before they were released to be separated and sent to their respective shovel stations. The Batch module was used to batch all the trucks to a particular parking station and then delayed to make up the break time by the Process module. The trucks were then separated into the respective truck assignments by the Separate module before they were sent to their respective shovel stations.

2.4 Shovel-Truck System Animation

In order to ensure that the shovel-truck model truly depicted the operations at Underlap Cutback Pit, various activities of the shovel-truck model were animated. The haul roads, dump sites and parking stations were drawn on the digital terrain model (DTM) of the pit as shown in Fig. 3. All route animations were then digitised on haul roads to depict truck movements while shovels, dumps and queues in the forms of resource (if shovels and dumps) and queues in Arena animations were located at respective positions in the pit and parking stations.

Miniature images of dump truck and excavator were used to represent the trucks and the shovel in the animation. Truck entity picture was chosen as the default entity picture type in the modelling process.

The Assign module was then used to change truck status to loaded and empty. The Route dialogue in the animation transfer tool bar was used to animate haul roads. The Resource button in the Animation tool bar was also used to define shovels and dumps pictures for animation. Pictures representing idle and busy status for the shovels and dumps were also assigned.

The routes and resources were all digitised on a DTM representing the pit. Fig. 3 shows the animation view in Arena.

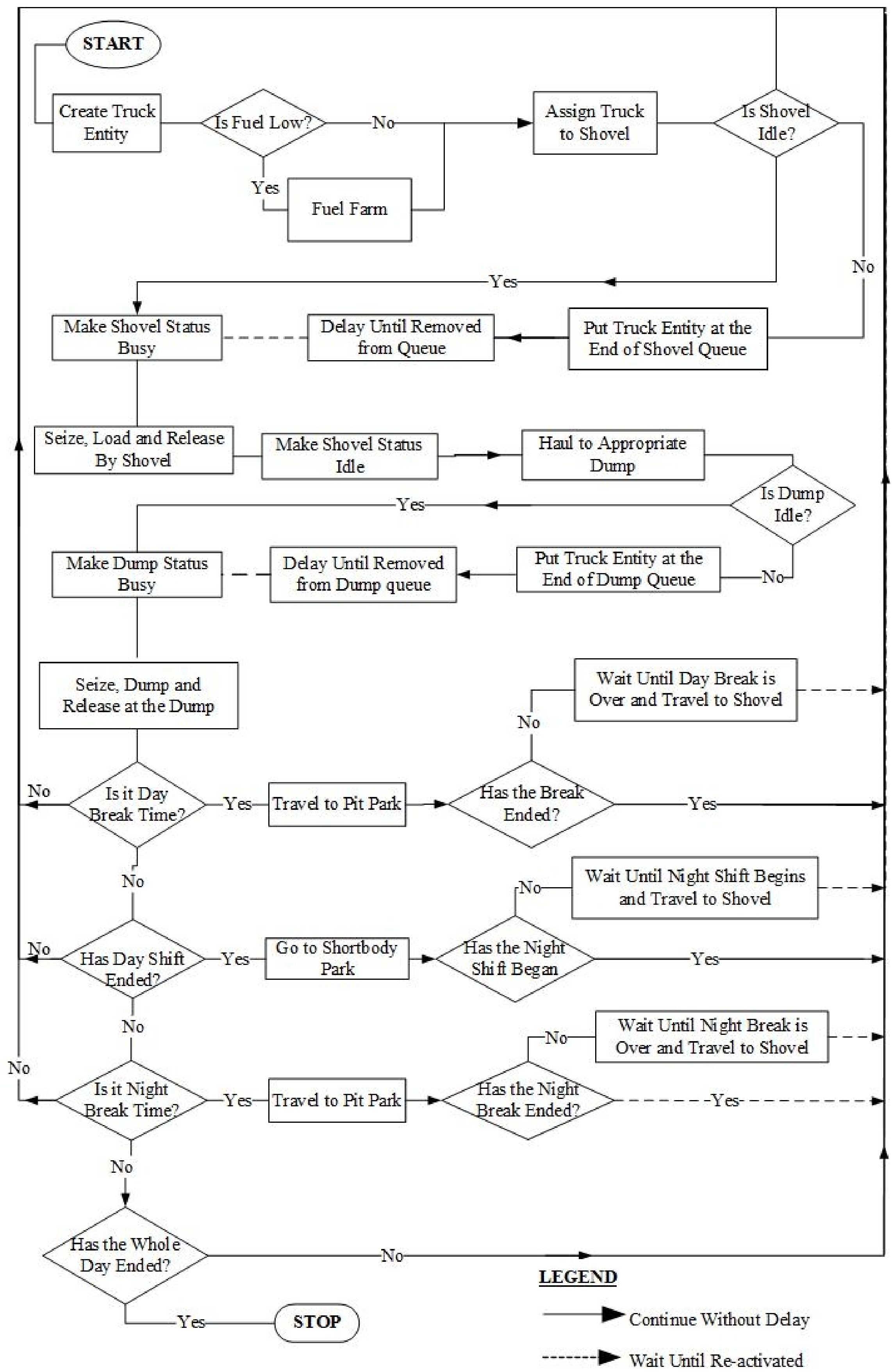

Fig. 2 Conceptual Model of the Shovel-Truck System at Underlap Cutback Pit

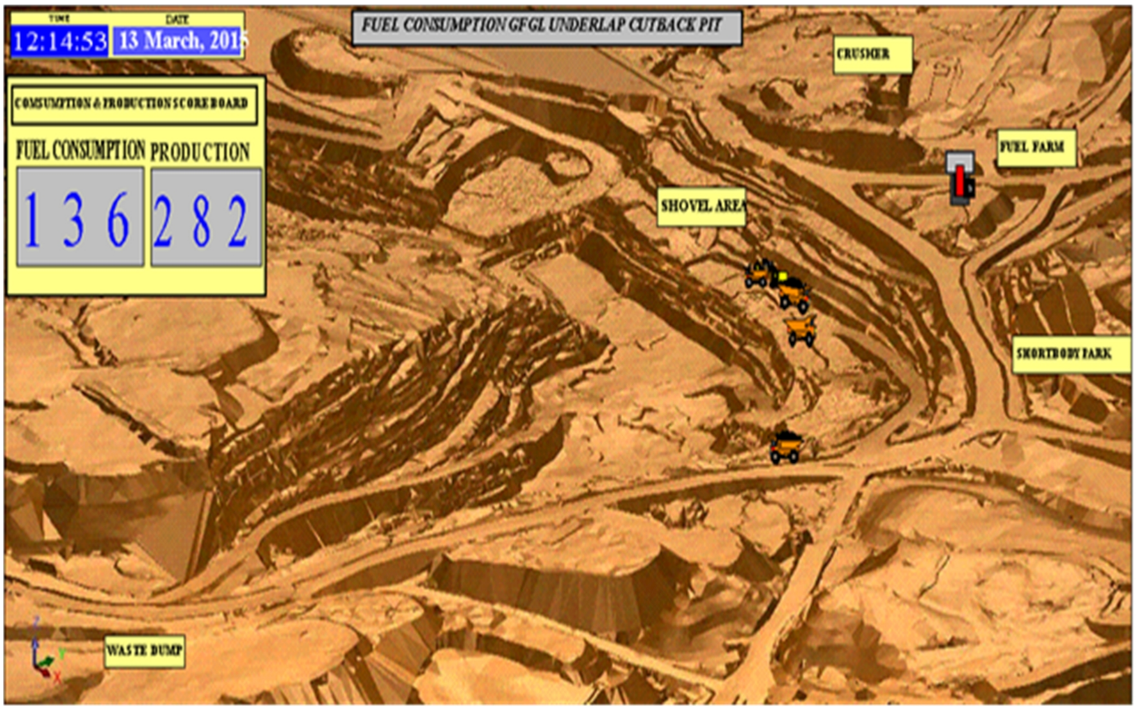

Fig. 3 Animation View of Underlap Cutback Pit Model

2.5 Model Execution

The shovel-truck model was executed using the statistical distributions and their corresponding expressions of the various cycle time elements. The model was then run for a day's (24 hours) operation including 30 minutes break for both shifts (day and night) and 30 minutes shift change for forty (40) replications.

2.6 Verification and Validation

The following steps were taken to verify and validate the shovel-truck model:

(i) Truck entity movement in the modules was carefully monitored during simulation run to verify the correct direction of movement at specified times and ensure synchronisation of transfer and delay times (loading, dumping or queuing).

(ii) The operations in the pit pertaining to shovels and trucks were also animated on representative DTM of the pit to ensure adequacy of the model in describing the shovel-truck system at Underlap Cutback Pit. The values of the various variables and the record modules were monitored throughout the execution of the model. Table 2 shows the results for the simulated and actual daily fuel consumption and production.

(iii) A walk-through was taken in the model to verify the correct order and logic of execution and monitor each module in the model using the step button.

3 Results and Discussion

The average daily fuel consumption for the excavator and the four CAT 785C trucks are shown in Table 2 with their half widths at 95% confidence interval.

Fig. 4 shows the simulated average monthly fuel consumption and production from Underlap Cutback Pit compared to the actual fuel consumption (litres) and production (tonnes) of the excavator and trucks.

Results of the simulated monthly fuel consumption and production are summarised in Fig. 4. The simulated monthly fuel consumption of the shovel and trucks are observed to be 62 000 litres and 136 127 litres, respectively, while the actual consumption is 64 362 litres for the excavator and 139 410 litres for the trucks. This results in inefficient over utilisation of 5 535 litres (thus, a variance 2.70% below the actual fuel consumption). Also, the simulated production is 701 849 tonnes against the actual of 650 515 tonnes, suggesting that optimising the fuel consumption by the shovel and trucks will impact positively on production.

Table 3 shows the recorded cycle time and the simulated cycle time per truck. The mean actual waiting and simulated times are 2.96 minutes and 1.61 minutes, respectively, with a corresponding fuel consumption of 4.06 litres and 2.43 litres, respectively. These translated into total monthly actual waiting time of 14 472 minutes which is equivalent to about 22 000 litres of fuel. The monthly simulated waiting time of 8 662 minutes corresponded to fuel consumption of 13 065 litres for the shovel-truck system. Hence, about 8 760 litres of fuel can be saved monthly if the shovel-truck system is optimised. Also, based on the simulation results, the average fuel consumption per tonne is 0.28 litres and that of the actual is 0.31 litres per tonne.

There are at least 10 excavators matched with a fleet of 48 dump trucks at various pits in the mine. Because the operational cycles of these excavators and trucks in other pits are not distinct from that of the Underlap Pit, the waiting time and the associated fuel consumption of the entire shovel-truck system of the mine can be very substantial. The significant fuel consumption attributed to truck waiting corroborates the findings by Siami-Irdemoosa and Dindarloo (2015). Hence, optimising the operations will significantly improve the cost of operations by eliminating the inefficient utilisation of fuel. The simulated model mimics the actual cycle and therefore can be adopted as a planning tool in forecasting and predicting the fuel consumption needs of the company.

Table 2 Daily Fuel Consumption and Production

	Actual	Simulated	
		Mean	Half Width
EX 16 Fuel Consumption (Litres)	2 145.40	2 066.88	±136.35
Trucks Fuel Consumption (Litres)	4 647.00	4 641.00	±458.00
Production (Tonnes)	21 683.83	23 394.96	±1 814.29

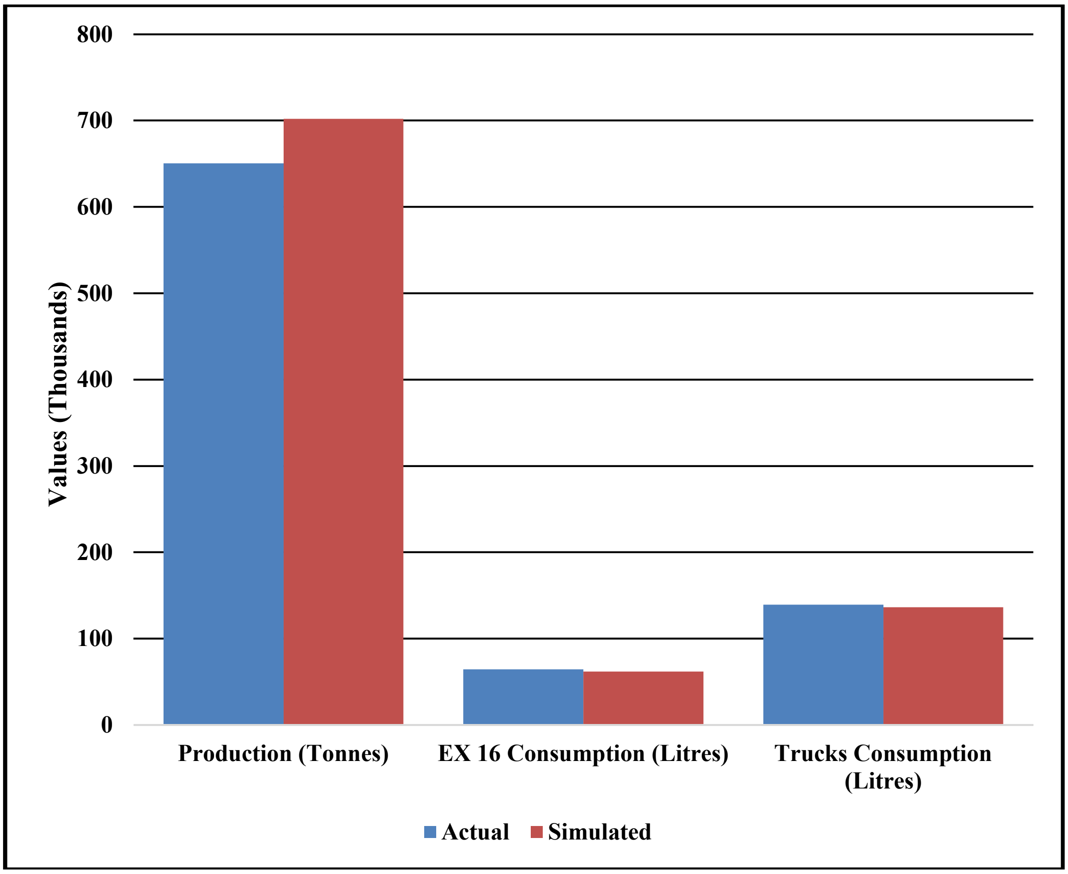

Fig. 4 Simulated and Actual Fuel Consumption

Table 3 Cycle and Waiting Times and their Corresponding Fuel Consumption

CYCLE No.	RECORDED		RECORDED		SIMULATED		SIMULATED	
	Waiting Time (Min)	Fuel Consumed (Litre)	Cycle Time (Min)	Fuel Consumed (Litre)	Waiting Time (Min)	Fuel Consumed (Litre)	Cycle Time (Min)	Fuel Consumed (Litre)
1	3.70	5.58	26.04	39.28	1.71	2.59	23.00	34.69
2	3.93	5.93	25.49	38.45	1.73	2.61	22.06	33.27
3	2.92	4.40	25.72	38.79	1.70	2.57	22.94	34.60
4	4.37	6.59	27.91	42.09	1.60	2.41	22.36	33.73
5	3.77	5.69	26.41	39.84	1.54	2.32	21.34	32.18
6	4.02	6.06	29.39	44.33	1.68	2.54	22.08	33.31
7	2.42	3.65	28.12	42.41	1.63	2.46	21.61	32.59
8	2.33	3.51	29.39	44.33	1.90	2.86	22.44	33.85
9	1.50	2.26	25.05	37.78	1.61	2.42	22.30	33.64
10	1.60	2.41	26.03	39.26	1.67	2.52	23.15	34.92
11	0.00	0.00	25.15	37.93	1.44	2.17	21.46	32.36
12	2.24	3.38	27.11	40.89	1.67	2.51	22.73	34.29
13	3.68	5.55	29.03	43.79	1.75	2.65	22.93	34.59
14	2.75	4.15	28.04	42.29	1.35	2.03	22.47	33.89
15	3.15	4.75	26.04	39.28	1.51	2.27	22.09	33.31
16	0.00	0.00	21.99	33.17	1.54	2.32	22.42	33.81
17	1.70	2.56	25.78	38.88	1.69	2.55	21.40	32.28
18	2.75	4.15	25.44	38.37	1.54	2.32	23.10	34.84
19	3.00	4.53	28.94	43.65	1.71	2.58	22.34	33.70
20	2.50	3.77	25.20	38.01	1.80	2.71	22.24	33.54
21	4.30	6.49	28.19	42.52	1.67	2.52	22.51	33.95
22	3.75	5.66	26.00	39.22	1.74	2.63	22.48	33.91
23	3.90	5.88	25.45	38.39	1.51	2.27	22.79	34.37
24	3.80	5.73	24.67	37.21	1.65	2.49	22.28	33.60
25	4.35	6.56	27.66	41.72	1.94	2.92	23.00	34.69
26	3.76	5.67	26.14	39.43	1.64	2.47	22.23	33.53
27	4.03	6.08	29.33	44.24	1.71	2.58	22.13	33.38
28	2.41	3.64	27.76	41.87	1.33	2.01	21.77	32.83
29	2.34	3.53	29.35	44.27	0.81	1.22	22.41	33.80
30	1.51	2.28	25.04	37.77	1.78	2.68	22.34	33.69
31	1.62	2.44	26.07	39.32	1.69	2.56	22.28	33.60
32	0.00	0.00	25.24	38.07	1.57	2.37	21.34	32.19
33	2.25	3.39	26.89	40.56	1.73	2.61	22.65	34.17
34	3.64	5.49	28.45	42.91	1.59	2.39	22.59	34.07
35	2.75	4.15	28.07	42.34	1.52	2.29	21.82	32.91
36	3.15	4.75	26.24	39.58	1.67	2.51	22.51	33.95
37	1.50	2.26	26.22	39.55	1.41	2.13	21.87	32.99
38	2.70	4.07	25.77	38.87	1.69	2.55	22.31	33.65
39	1.75	2.64	25.30	38.16	1.34	2.02	22.47	33.90
40	1.80	2.72	26.10	39.37	1.71	2.59	22.73	34.28
Total	107.64	163.36	1066.21	1608.19	64.47	97.27	892.95	1346.87
Average	2.69	4.06	26.66	40.20	1.61	2.43	22.32	33.67

4 Conclusions and Recommendation

Fuel consumption by the shovel-truck system at Gold Fields Ghana Limited in Tarkwa, Ghana was studied using stochastic simulation modelling. Due to certain constraints, only one shovel-truck system (single shovel with a fleet of four trucks) was considered. At 95% confidence interval, the monthly simulated fuel consumption by the shovel-truck system was found to be about 198 127 litres against the actual fuel consumption of 203 772 litres, registering a variance of -2.70%. The monthly stimulated fuel consumption by the shovel was 62 000 litres, while the actual fuel consumption was 64 362 litres. The simulated fuel consumption by the four trucks was 136 127 litres, while the actual fuel consumption was 139 410 litres. Simulating the monthly waiting times of the trucks resulted in reduction of fuel consumption from the actual estimated 22 000 litres to about 13 000 litres. The study suggests that optimising material handling operations would minimize fuel consumption expense and improve production.

Optimising the entire shovel-truck system at the mine will result in significant fuel cost savings; given that the mine operates at least 10 other shovels and 48 trucks in similar operation pattern. Future studies include improving the current model into a more holistic and robust fuel consumption model for the entire shovel-truck system of the mine. Such model will incorporate variabilities in fuel consumption per activity of the system. It is anticipated that an optimised process will reduce the consumption of fuel and potentially reflect in the reduction of greenhouse gas emissions commonly associated with the combustion of fossil-based fuels.

References

Adak, P., Sahu, R. and Elumalai, S. P. (2016), "Development of Emission Factors for Motorcycles and Shared Auto-rickshaws Using Real-world Driving Cycle for a typical Indian City", *Science of The Total Environment,* Vol. 544, pp. 299-308.

Altiok, T. and Melamed, B. (2007), *Simulation Modeling and Analysis with Arena*, Elsevier Academic Press, New York, USA, 440pp.

Anglani, A., Grieco, A., Pacella, M. and Tolio, T. (2002), "Object-Oriented Modelling and Simulation of Flexible Manufacturing Systems: A Rule-based Procedure", *Simulation Modelling Practice and Theory,* Vol. 10, Issue 3, pp. 209-234.

Awuah-Offei, K. (2012), "Can Discrete Event Simulation Help You Improve Your Operation?"*http://sphinxminingsystems.com/blog/?p=78.* Accessed: January 30, 2015.

Awuah-Offei, K., Osei, B. and Askari-Nasab, H. (2012), "Improving Truck-Shovel Energy Efficiency Through Discrete Event Modeling", *Society of Mining, Metallurgy & Exploration (SME) Annual Meeting,* Seattle, WA., Preprint 12-069, pp. 1 – 6

Fioroni, M. M., Bianchi, T. J., Pinto, L. R., Franzese, L. A. G., Luiz Ezawa, L. and Miranda, G. (2008), "Concurrent Simulation and Optimization Models for Mining Planning", *Proceedings of the 2008 Winter Simulation Conference,* Mason, S. J. (ed.), Florida, USA, pp. 759 – 767.

Heide, C. H. and Mohazzabi, P. (2013), "Fuel Economy of a Vehicle as a Function of Airspeed: The Concept of Parallel Corridors", *International Journal of Energy and Environmental Engineering,* 2013, pp. 1 – 9.

Hogg, G. A., Pulkki, R. E. and Ackerman, P. A. (2010), "Multi-stem Mechanized Harvesting Operation Analysis–Application of Arena 9 Discrete-event Simulation Software in Zululand, South Africa", *International Journal of Forest Engineering,* Vol. 21, Issue 2, pp.14-22.

Jun, J. B., Jacobson, S. H. and Swisher, J. R. (1999), "Application of Discrete-event Simulation in Health Care Clinics: A Survey", *Journal of the Operational Research Society,* pp. 109-123.

Kecojevic, V. and Komljenovic, D. (2010), "Haul Truck Fuel Consumption and CO_2 Emission under Various Engine Load Conditions", *MınıngEngıneerıng Magazine,* December, 2010, pp. 44 – 48.

Koellner, W. G., Brown, G. M., Rodríguez, J., Pontt, J., Cortés, P. and Miranda, H. (2004), "Recent Advances in Mining Haul Trucks", *Industrial Electronics, IEEE Transactions,* Vol. 51, Issue 2, pp. 321-329.

Koenig, R. L., Marinopoulos, N. and Olsson, B. R. (2002), "Using Reliability Modelling to Confirm Plant Design Capacity", *Proceedings of Metallurgical Plant Design and Operating Strategies,* Sydney, NSW, pp. 248 - 260.

Komashie, A. and Mousavi, A. (2005), "Modeling Emergency Departments Using Discrete Event Simulation Techniques", *In Proceedings of the 37th conference on Winter simulation,* Winter Simulation Conference, pp. 2681-2685.

Krause, A. and Musingwini, C. (2007), "Modelling Open Pit Shovel-Truck Systems Using the Machine Repair Model", *The Journal of The Southern African Institute of Mining and Metallurgy,* Vol. 107, August 2007, pp. 469-476.

Kuhl, M. E., Kistner, J., Costantini, K. and Sudit, M. (2007), "Cyber-Attack Modelling and Simulation for Network Security Analysis", *In Proceedings of the 39th Conference on Winter Simulation,* December, IEEE Press, pp. 1180-1188.

Kumar, S. and Phrommathed, P. (2006), "Improving a Manufacturing Process by Mapping and Simulation of Critical Operations", *Journal of Manufacturing Technology Management,* Vol. 17, Issue 1, pp. 104-132.

Li, S., Dimitrakopoulos, R., Scott, J. R. and Dunn, D. (2004), "Quantification of Geological Uncertainty and Risk using Stochastic Simulation and Applications in the Coal Mining Industry" In Orebody Modelling and Strategic Mine Planning-Uncertainty and Risk Management International Symposium 2004, *The Australasian Institute of Mining and Metallurgy,* pp. 185-192.

Lin, H., Cui, X., Yu, Q. and Yang, S. (2011), "Experimental Study on Diesel Vehicle's Fuel Consumption Feature While Coasting on Level Road", *Proceedings of International Conference,* Part 1, CSIE 2011, Shen, G. and Huang, X. (eds.), Zhengzhou, China, 21 - 22 May, 2011. pp 264 – 270.

Nel, S., Kizil, M. S. and Knights, P. (2011), "Improving Truck-Shovel Matching", *Proceedings of the 35th APCOM Symposium,* Wollongong, NSW, pp. 381 – 391.

Norgate, T. and Haque, N. (2010), "Energy and greenhouse gas impacts of mining and mineral processing operations", *Journal of Cleaner Production,* Vol. 18, Issue 3, pp. 266-274.

Parreira, J. (2013), "An Interactive Simulation Model to Compare an Autonomous Haulage Truck System with a Manually-Operated System", *Unpublished Doctoral Dissertation,* University of British Columbia, Vancouver, 212pp.

Patil, K., Jin, K. and Li, H. (2011), "Arena Simulation Model for Multi Echelon Inventory System in Supply Chain Management", *In Industrial Engineering and Engineering Management (IEEM),* 2011 IEEE International Conference, December, IEEE, pp. 1214-1217.

Rogers, P. (2002), "Optimum-Seeking Simulation in the Design and Control of Manufacturing Systems: Experience with OptQuest for Arena", *In Simulation Conference, 2002. Proceedings of the Winter,* December, IEEE, Vol. 2, pp. 1142-1150.

Shelswell, K. J., Fitzgerald, J. and Labrecque, P. O. (2013), "Discrete Event Simulation Modelling versus TKM Analysis of a Mine Operating with a Hybrid Material Movement Practice Consisting of Truck Haulage and Skipping", *Proceedings of CIM Convention,* Toronto, 2013, 9pp.

Siami-Irdemoosa, E. and Dindarloo, S. R. (2015), "Prediction of Fuel Consumption of Mining Dump Trucks: A Neural Networks Approach", *Applied Energy* 151, pp. 77–84.

Wang, T., Guinet, A., Belaidi, A. and Besombes, B. (2009), "Modelling and Simulation of Emergency Services with ARIS and Arena. Case Study: The Emergency Department of Saint Joseph and Saint Luc Hospital", *Production Planning and Control,* Vol. 20, Issue 6, pp. 484-495.

Zeng, Q. and Yang, Z. (2009), "Integrating Simulation and Optimization to Schedule Loading Operations in Container Terminals", *Computers & Operations Research,* Vol. 36, Issue 6, pp. 1935-1944.

Author

Nelson K. Dumakor-Dupey holds BSc in Mining Engineering from University of Mines and Technology. He is currently a Demonstrator and an MPhil Candidate in the Mining Engineering Department of the University of Mines and Technology, Tarkwa, Ghana. Areas of his research interest are Modelling and Simulation of Mining Systems, and Sustainable Mining.

Victor A. Temeng is an Associate Professor in Mining Engineering at the University of Mines and Technology (UMaT), Tarkwa. He obtained his BSc (Hons.) and Postgraduate Diploma in Mining Engineering degrees from Kwame Nkrumah University of Science and Technology School of Mines, Ghana. He holds MSc degree from the University of Zambia and PhD degree from the Michigan Technological University. He is a member of the Ghana Institution of Engineers (GhIE). His areas of specialisation include Operations Research, Materials Handling and Computer Applications.

Kenneth J. Bansah is a Graduate Research Assistant and PhD candidate at Missouri University of Science and Technology, Missouri, USA. He holds an MPhil Degree in Mining Engineering from the University of Mines and Technology, Ghana and BSc. in Mining Engineering from the Kwame Nkrumah University of Science and Technology, Ghana.. His current research areas include blast optimization, small scale mining, environmental and engineering applications of geophysics, occupational health and hygiene, safety and environmental management.