Monte Carlo reliability simulation of underground mining drilling rig

Hussan Al-Chalabi
Division of Operation and Maintenance Engineering
Luleå University of Technology
971 87 Luleå, Sweden
+46 (0)920-49 29 45
hussan.hamodi@ltu.se

Hadi Hoseinie
Division of Operation and Maintenance Engineering
Luleå University of Technology
971 87 Luleå, Sweden
+46 (0)920-49 34 28
hadi.hoseinie@ltu.se

Jan Lundberg
Division of Operation and Maintenance Engineering
Luleå University of Technology
971 87 Luleå, Sweden
+46 (0)920-49 17 48
Jan.Lundberg@ltu.se

ABSTRACT

Drilling rigs are widely used in mine development or construction and tunnel engineering projects. The rig consists of 12 subsystems in a series configuration and can be driven by diesel or electrical engines. This paper uses the Kamat-Riley (K-R) event-based Monte Carlo simulation method to perform reliability analysis of an underground mine drilling rig. For data analysis and to increase statistical accuracy, the paper discusses three case studies in an underground mine in Sweden. Researchers built a process to programme the simulation process and used MATLAB™ software to run simulations. The results showed the simulation approach is applicable to the reliability analysis of this rig. Moreover, the reliability of all rigs reaches almost zero value after 50 hours of operation. Finally, the differences between the reliability of the studied fleet of drilling rigs are a maximum 10%. Therefore, all maintenance or spare part planning issues can be managed in a similar way.

Keywords

Drilling rigs, K-R method, Monte Carlo simulation, Reliability, Simulation, Underground mines.

1. INTRODUCTION

Underground mines are a main source of minerals. The growing demand for metals as a result of modern lifestyles and ongoing industrial development has focused attention on factors affecting the extraction of minerals. One of the most important factors is the unscheduled stoppage of machines used in the extraction of ore [1]. Economic globalisation is increasing competition among mining companies, pushing them to achieve higher production rates by increasing automation and mechanisation and using new and more effective equipment. This forces companies to buy more reliable capital equipment with higher performance capabilities; naturally, these are more expensive. At the same time, the equipment used in underground mining industries is subject to degradation throughout its operating life; this increases the operating and maintenance costs and reduces production rates, causing a negative economic effect as equipment ages [2].

The drilling rig is very important to the extraction process. At its most basic level, drilling is the process of making holes in the mining room face, but reliable and accurate drilling operation facilitates the rest of the production chain and improves the economic and safety issues of the mine. All drilling machines for mining applications are composed of similar operational design units, including cabin, boom, rock drill, feeder, service platform, front jacks, hydraulic pump, rear jack, electric cabinet, hose reeling unit, cable reeling unit, diesel engine, hydraulic oil reservoir, operator panel and water tank. Drilling rigs manufactured by different companies have different technical characteristics, e.g. capacity and power. Based on the operating manuals, field observations and maintenance reports from the collaborating mine, in this study, the drilling rig is considered a system divided into several subsystems and connected in series configuration; if any subsystem fails, the operator will stop the rig to maintain it. Given this configuration, having good knowledge about these rigs and properly maintaining them is essential for a reliable drilling operation and assured production.

Collecting data, analysing data and making decisions are time consuming process, but they should be done during any reliability study. The reliability analysis of mining machines is especially difficult in practice because of the special operation and maintenance environment and the work pressure in mines [3].

This paper uses stochastic simulation to evaluate the reliability of three drilling machines used in an underground mine in Sweden. Stochastic simulation is a suitable technique to assess the reliability of a system and can be applied in two ways [4, 5]:

- Sequential approach by examining each basic interval of the simulated period in chronological order, and
- Random approach by examining randomly chosen basic intervals of the system's lifetime.

The second approach, usually known as "Monte Carlo" method, is selected for this paper. This is a numerical method which allows the solution of mathematical and technical problems by means of system probabilistic models and simulation of random variables.

Many researchers have studied the reliability and maintainability of mining equipment and its failure behaviour. For example, Kumar et al. (1989) analysed the operational reliability of a fleet of diesel operated load-haul dump (LHD) machines in Kiruna mine in Sweden [6]. Later, Kumar et al. (1992) performed reliability analysis on the power transmission cables of electric mine loaders in Sweden [7]. Reliability assessment of mining equipment was performed by Vagenas and Nuziale (2001); using genetic algorithms, they developed and tested mobile mining equipment reliability assessment models [8]. Vayenas and Xiangxi (2009) studied the availability of 13 LHD machines in an underground mine. They were interested in the influence of machine downtime on productivity and operation costs and used a reliability-based approach and a basic maintenance approach to determine the machine's availability [9]. More recently, Gustafson et al. (2012) used fault tree analysis (FTA) to analyse the idle times of automated load-haul-dump LHD machines at a Swedish underground mine [10]. Finally, Hoseinie et al. (2012) performed reliability modelling on the drum Shearer machine used at Taba's coal mine in the central desert of Iran and analysed the failure rate of the machine's subsystems [11].

Although there are many reliability and maintainability studies of underground mining equipment, no one has looked specifically at drilling machines. Given the importance of underground mining mobile equipment for production, not to mention the complexity of the equipment and the harsh mining environment, reliability analysis of the drilling rig must meet rigorous requirements. Thus, the aim of this paper is to analyse and compare the reliability of several drilling rigs to show the Kamat-Riley (K-R) event-based Monte Carlo simulation method can be used to simulate the reliability of repairable complex systems based on available data from the case study mining company. The paper also aims to shed light on the reliability behaviour of the mining drilling rig to enhance decision-making, improve reliability and reduce downtime.

2. MINING DRILLING RIG

A mining drilling rig is used to dig holes in the ground. For example, mobile drilling rigs can be used to make tunnels and underground facilities, and small or medium-sized mobile drilling rigs are appropriate for mineral exploration. Mining drilling rigs are used for two main purposes, namely production drilling (for processes in the mining production cycle such as bolting) and exploration drilling (to identify the location of minerals). Figure 1 illustrates the process cycle for drift mining; as the figure shows, drilling is a key step. From an economic viewpoint, drilling rigs make an important contribution to the mine's production rate but they have a high acquisition, maintenance and operating cost and represent a possible critical bottleneck for production [12].

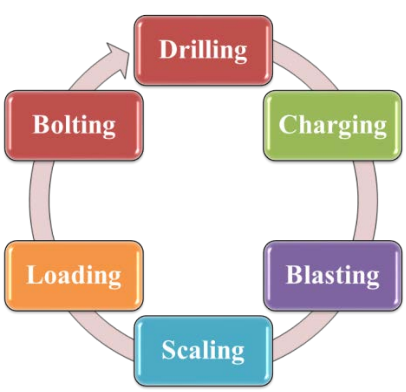

Figure 1. A typical drift mining process cycle

Economic competition has pressured mining companies into achieving higher production rates by enhancing the techniques of drilling and blasting and increasing mechanisation and automation. Historical data over the period of one year from an underground mine in Sweden show that more than 15 percent of unplanned downtime of mobile equipment is related to the drilling rigs, with the greater part of the downtime attributed to the poor reliability of their components or subsystems. Other factors contributing to downtime include the harsh work environment and the operating context. Given this combination of factors, the drilling rig often represents a bottleneck in the mining production cycle and, thus, is becoming an important research topic.

3. DATA COLLECTION AND ANALYSIS

The failure data used in this paper were collected over a period of two years (2009-2011). The source of the data is the database of an underground mine in Sweden participating in the study. This database belongs to the MAXIMO system, a computerised maintenance management system (CMMS). In this research study, the time to failure data (TTF data) and the time to repair data (TTR data) of three drilling rigs and their subsystems were arranged in chronological order so that statistical analysis could find trends in the failure and repair data.

The first step in analysing the data was calculation of the times between failures (TBFs) for the system. In the CMMS, the failure data are recorded based on calendar time. Since drilling is not a continuous process, the TBFs were estimated by considering the utilisation of each rig. Reliability and maintainability data analysis is usually based on the assumption that the TBF and TTR data are independent and identically distributed (iid) in the time domain. It was critical to conduct a formal verification analysis of the assumption that the TBF and TTR data were iid; otherwise completely wrong conclusions could be drawn [13, 14]. Accordingly, the next step, after sorting and classifying the TBF and TTR data based on the subsystem level, was validation of the iid assumption. The failure data were tested for trends with the Laplace trend test. This test is used to determine whether a data set is identically distributed [14]. If such a trend is observed, classical statistical techniques for reliability analysis may not be appropriate, and a non-stationary model such as the non-homogenous Poisson process (NHPP) must be fitted [13-18]. Otherwise, the serial correlation test can be used to test the dependence of the failure data. A dependence test determines whether successive failures are dependent in data without a long-term trend [14]. If a dependence between successive failure data is observed, a branching Poisson process (BPP) model can be used [13]. If dependence is not observed, the iid assumption is valid. In this study, after testing the validity of the iid assumption, we examined different types of statistical distributions and estimated their parameters using the Easy Fit and Minitab software. The goodness of fit of the distribution was tested by using the Kolmogorov-Smirnov (K-S) test with the Easy Fit software. In the present paper, all statistical tests used a significance level (α) equal to 0.05.

4. RELIABILITY ANALYSIS USING MONTE CARLO SIMULATION METHOD

Following the process described above, after classifying and sorting the data, we calculated the TBF of each subsystem and performed statistical validation to look for the presence of structures or trends in the failure data using Laplace trend and serial correlation tests. The Laplace trend test was used to test the hypothesis that a trend did not exist within the TBF data. We calculated the test statistic U for the TBFs of the drilling rig subsystems to be at a significant level of 0.05. From the standard normal tables, with a significant level of 0.05, the critical value is equal to 1.96. If $-1.96<U<1.96$, we accepted the hypothesis of no trend within the TBF data. After applying the trend test for the critical components of the studied rigs, we found no trend within the TBF data; for example, U was equal to 0.55 in the feeder of rig A used in the collaborating mine.

We performed a serial correlation test of the TBF data of the drilling rigs and their subsystems to check the dependence of the TBF data. To this end, we plotted the ith TBF against the (i-1)th TBF. We then tested the significance of the correlation by calculating the (r) value and comparing it with the critical (r) value obtained from the correlation tables. The results of the serial correlation test of the above component (i.e. the feeder) are given in Figure 2. Since the points in the figure are randomly scattered, the failure data can be assumed to be independently distributed. The (r) value is equal to 0.05, while the critical value of (r) from the correlation tables at the significance level alpha = 0.05 and a degree of freedom of 30 for a two-tailed test is equal to 0.364. We can conclude that the correlation between the TBFs of this subsystem is statistically not significant (i.e. no correlation exists), since r < the critical r.

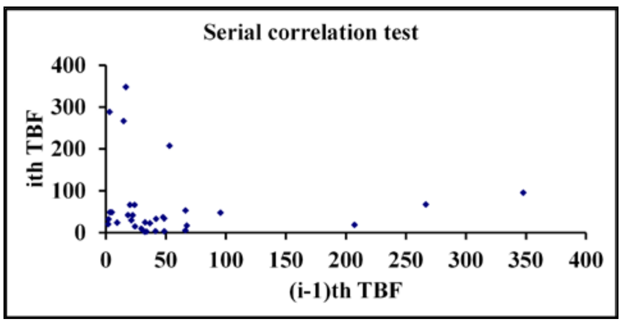

Figure 2. Serial correlation test for the feeder of the drilling rig A

The results of the tests showed all subsystems in three studied rigs are free from trends and serial correlations and are identically and independently distributed (iid); therefore, the renewal process is the best way to perform reliability analysis on these subsystems. We examined various types of statistical distributions and estimated their parameters using the Easy Fit and Minitab software. The best fitted failure density functions are shown in Tables 1-3.

Table 1. Data analysis of subsystems of rig A

Rig A		
Subsystems	**Best fitted function**	**Parameters**
Hoses	Weibull 2P	$\alpha=0.92$ $\beta=20.75$
Rock Drill	Weibull 2P	$\alpha=0.98$ $\beta=69.1$
Feeder	Lognormal 3P	$\sigma=1.26$ $\mu=3.4$ $\gamma=-0.14$
Boom	Weibull 2P	$\alpha=1.04$ $\beta=146.28$
Accumulators	Normal	$\sigma=197.41$ $\mu=256.16$
Hydraulic System	Gamma	$\alpha=0,336$ $\beta=1047$
Valves	Lognormal	$\sigma=1.17$ $\mu=4.36$
Control Panel	Exponential	$\lambda=0.008$
Water System	Lognormal	$\sigma=1.27$ $\mu=5.17$

Table 2. Data analysis of subsystems of rig B

Rig B		
Subsystems	**Best fitted function**	**Parameters**
Hoses	Weibull 3P	$\alpha=0.95$ $\beta=55.53$ $\gamma=0.6$
Rock Drill	Lognormal	$\sigma=1.26$ $\mu=3,27$
Feeder	Weibull 2P	$\alpha=0.82$ $\beta=42.47$
Boom	Exponential	$\lambda=0.006$
Accumulators	Normal	$\sigma=214.1$ $\mu=300.5$
Cable System	Weibull 2P	$\alpha=1.09$ $\beta=339.7$
Hydraulic System	Weibull 3P	$\alpha=0.6$ $\beta=148.3$ $\gamma=16.92$
Steering System	Weibull 3P	$\alpha=1.15$ $\beta=112.9$ $\gamma=4.27$

Table 3. Data analysis of subsystems of rig C

Rig C		
Subsystems	**Best fitted function**	**Parameters**
Hoses	Lognormal 3P	$\sigma=1.072$ $\mu=3.12$ $\gamma=-1.19$
Rock Drill	Gamma 3P	$\alpha=1.13$ $\beta=52.61$
Feeder	Exponential	$\lambda=0.018$
Boom	Weibull 3P	$\alpha=0.58$ $\beta=122.7$ $\gamma=19.04$
Accumulators	Weibull 2P	$\alpha=1.48$ $\beta=502.1$
Cable System	Exponential	$\lambda=0.002$
Hydraulic System	Lognormal 3P	$\sigma=0.77$ $\mu=5.45$ $\gamma= -66.72$
Steering System	Lognormal 3P	$\sigma=0.62$ $\mu=5.22$ $\gamma=-37.7$
Generator	Weibull 2P	$\alpha=0.999$ $\beta=299.82$

The Monte Carlo simulation method plays an important role in system reliability assessment and optimal maintenance of large-scale complex networks but, in general, there are four major difficulties in evaluation [5]:

- System reliability structure may be very complicated;
- Subsystems may follow different failure distributions;
- Subsystems may have arbitrary failure and repair distributions for maintained systems; and
- Failure data of subsystems are sometimes not sufficient and sample size of life test or field population tends to be small.

Among the various Monte Carlo reliability simulation algorithms, the K-R algorithm developed by Kamat and Raily [19] can be considered the most general and basic; other suggested methods for reliability simulation are merely modified forms of this method [20]. Therefore, the K-R method has been used for the reliability simulation of drilling rigs in this paper.

In this method, the failure times for individual components are generated based on the defined failure distribution function and then used to determine the success or failure of the system. The stages of the K-R method are [19]:

1. Find all minimal tie-sets from system reliability block diagram (RBD). Assume we must obtain system reliability interval estimates at some time point *t*.
2. From the life distribution of each subsystem, generate a random failure time t_i where *i* represents the i^{th} subsystem, 0 <*i*< n.
3. Compare t_i with t for all subsystems. If t_i>t, this indicates that at the time, *t* subsystem *i* functions properly; if t_i<*t*, the subsystem *i* has failed.
4. Determine whether the whole system is functioning or down according to the statues of its subsystems at *t* from step (3). Check all subsystems in a minimal tie-set. If all are operational, the system is operating properly at time *t*. If one or more fails, the tie-set is broken (failure) at *t*. Check the next minimal tie-set until an unbroken one appears, which means the system is operational at *t*. If all minimal tie-sets are broken, the system fails at *t*.
5. Repeat steps (2), (3), (4) for, say, *N* times. Count failure and success numbers of the system respectively: N_S (t) and N_F (t). Note that $N = N_S(t) + N_F(t)$.
6. The system reliability point estimate corresponding to *t* is given by equation (1):

$$\hat{R}(t) = \frac{N_S(t)}{N_S(t) + N_F(t)} \qquad (1)$$

5. RESULTS AND DISCUSSION

To ensure fast and reliable calculations during the simulation process, we prepared a computer program using MATLAB™ software. For each rig, we ran the program for different operation times with the iteration number of 10000 and achieved a reliability plot for each. Figure 3 shows the reliability plots of all three rigs achieved using the simulation method in one area. As can be seen in this figure, rig A has the lowest reliability of the three drilling rigs. However, the difference is small; the maximum value is 10%, at about 15 hours. All studied rigs are almost equal in reliability in the period of high reliability operation (from time 0 to 5 hours) and in the period of very low reliability operation (after 35 hours). The reliability of all rigs decreases by almost zero after 50 hours. The main reason for this result is that the collaborating mining company bought the three rigs in the period 2003-2005 but kept failure and repair data in CMMS only from 2009. Therefore, the rigs were already in the wear-out failure period when the data were collected for this study; see Figure 4. It is also obvious from Figure 3 that the reliability plot of rigs B and C are so extremely close that they are almost the same.

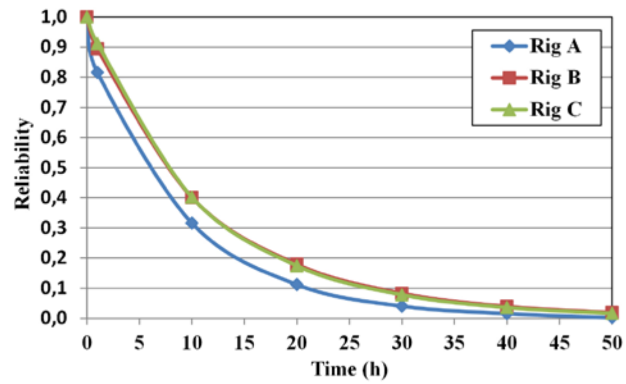

Figure 3. Reliability plots of all rigs

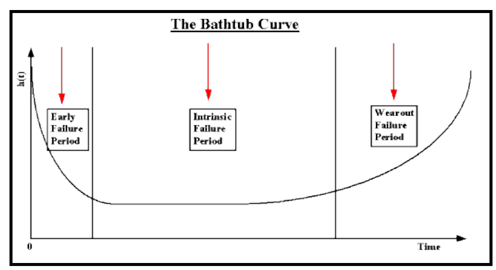

Figure 4. Bathtub curve (adapted from [21])

6. CONCLUSIONS

In this paper, we analysed the reliability of three drilling rigs in a Swedish underground mine using the Kamat-Riley (K-R) simulation method. We ran the simulation process based on the series configuration of the repairable subsystems for the drilling rigs. To set up the simulation process, we created a computer program in MATLAB™ software. The results of simulation suggested the reliability of all rigs reduces to zero at about 50h, possibly because the three rigs were already in their wear-out failure period when the data were collected for this study. As this short time shows, this important mining machine needs serious maintenance and servicing planning to reduce its downtime. Our overall aim was to test the applicability of the Monte Carlo simulation method to the analysis of the rig's reliability; we found this method is appropriate for reliability studies. It is time consuming, however, and hence best suited for large, complicated systems. Future studies should consider a comprehensive examination of maintenance scheduling and cost analysis of the underground drilling rigs.

7. ACKNOWLEDGMENTS

The maintenance personnel and maintenance management system employees at Boliden AB and Atlas Copco who helped the authors in this research are thanked for their support.

8. REFERENCES

[1] Al-Chalabi, H., Lundberg, J., Wijaya, A., and Ghodrati, B. (2014). "Downtime analysis of drilling machines and suggestions for improvements". *Journal of Quality in Maintenance Engineering*, *20*(4), pp. 306-332.

[2] Al-Chalabi, H., Lundberg, J., Jonsson, A. and Ahmadi, A. (2014). "Case Study: Model for economic lifetime of drilling machines in the Swedish mining industry". *Engineering* Economist. http://dx.doi.org/10.1080/0013791X.2014.952466

[3] Krishna Mohan K., Verma A. K., Srividya A., and Ljubisa P. (2010). "Integration of black- box and white-box modeling approaches for software reliability estimation". *International* Journal *of Reliability, Quality and Safety Engineering*, 17(3), pp. 261-273.

[4] Hoseinie S. H., Ataie M., Khalokakaie R., Ghodrati B., and Kumar U. (2012). "Reliability Analysis of Cable System of Drum Shearer Using Power Law Process Model". *International* Journal *of Mining, Reclamation and Environment*, 26(4), pp. 309-323.

[5] Wang, H., and Pham, H. (1997)." Survey of Reliability and Availability Evaluation of Complex Networks Using Monte Carlo Techniques". *Microelectronics Reliability*, 37(2), 187-209.

[6] Kumar, U., Klefsjö, B. and Granholm, S. (1989). "Reliability investigation for a fleet of load haul dump machines in a Swedish mine". *Reliability engineering system safety*, 26(4), pp. 341-361.

[7] Kumar, D., Klefsjo, B. and Kumar, U. (1992). "Reliability analysis of power transmission cables of electric mine loaders using the proportional hazards model". *Reliability* engineering *system safety, 37(3), pp. 217-222.*

[8] Vagenas, N., and Nuziale, T. (2001). "Genetic algorithms for reliability assessment of mining equipment". *Journal of quality in maintenance engineering*, 7(4), pp. 302-311.

[9] Vayenas, N. and Xiangxi, W. (2009). "Maintenance and reliability analysis of a fleet of load-haul-dump vehicles in an underground hard rock mine". *International Journal of* Mining, *Reclamation and Environment*, 23(3), pp. 227-238.

[10] Gustafson, A., Schunnesson, H., Galar, D. and Kumar, U. (2012). "The influence of the operating environment on manual and automated load-haul-dump machine: a fault tree analysis". *International Journal of Mining, Reclamation and Environment*, DOI:10.1080/1755182X.2011.651371.

[11] Hoseinie, S.H., Ataei, M., Khalokakaie, R., Ghodrati, B. and Kumar, U. (2012). "Reliability analysis of drum shearer machine at mechanized longwall mines". *Journal of* quality *in maintenance engineering*, 18(1), pp. 98-119.

[12] Al-Chalabi, H. (2014). *Reliability and Life Cycle Cost Modelling of Mining Drilling Rigs*. Doctoral thesis, Lulea University of Technology, Sweden.

[13] Ascher, H., and Feingold, H. (1984). *Repairable systems reliability: modeling, inference,* misconceptions *and their causes.* Marcell Dekker, New York.

[14] Kumar, U., and Klefsjö, B. (1992). "Reliability analysis of hydraulic systems of LHD machines using the power law process model". *Reliability Engineering and System Safety*, 35(3), pp. 217–224.

[15] Modarres, M. (2006). *Risk Analysis in Engineering: Techniques, Tools, and Trends*. Taylor& Francis Group, Boca Raton.

[16] Birolini, A. (2007). *Reliability Engineering: Theory and Practice.* Fifth edition, Springer-Verlag, Heidelberg, New York.

[17] Louit, D. M., Pascual, R., and Jardine, A. K. (2009). "A practical procedure for the selection of time-to-failure models based on the assessment of trends in maintenance data". *Reliability Engineering and System Safety*, 94(10), pp. 1618-1628.

[18] Ghosh, S., and Majumdar, S. K. (2011). "Reliability modeling and prediction using classical and Bayesian approach: A case study". *International Journal of Quality & Reliability Management*, 28(5), pp. 556-586.

[19] Kamat, S. J., and Riley, M. W. (1975). "Determination of reliability using event-based Monte Carlo simulation". *IEEE Transactions on Reliability*, 24(1), pp. 73-75.

[20] Hoseinie S. H., Khalokakaie R., Ataie M., Ghodrati B., and Kumar U. (2013). "Monte Carlo reliability simulation of coal shearer machine". *International Journal of Performability Engineering*, 9(5), pp.487- 494.

[21] Blischke, W., and Murthy, D. (2003). *Case Studies in Reliability and Maintenance*. John Wiley & Sons, Hoboken, New Jersey.