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Abstract

Purpose – The purpose of this paper is to analyse and compare the downtime of four drilling machines used in two underground mines in Sweden. The downtime of these machines was compared to show what problems affect downtime and which strategies should be applied to reduce it.
Design/methodology/approach – The study collects failure data from a two-year period for four drilling machines and performs reliability analysis. It also performs downtime analysis utilising a log-log diagram with a confidence interval.
Findings – There are notable differences in the downtime of most of the studied components for all machines. The hoses and feeder have relatively high downtime. Depending on their downtime, the significant components can be ranked in three groups. The downtime of the studied components is due to reliability problems. The study suggests the need to improve the reliability of critical components to reduce the downtime of drilling machines.
Originality/value – The method of analysing the downtime, identifying dominant factors and the interval estimation for the downtime, has never been studied on drilling machines. The research proposed in this paper provides a general method to link downtime analysis with potential component improvement. To increase the statistical accuracy; four case studies was performed in two different mines with completely different working environment and ore properties. Using the above method showed which components need to be improved and suggestions for improvement was proposed and will be implemented accordingly.

Keywords Reliability analysis, Confidence interval, Downtime analysis, Drilling machine
Paper type Research paper

1. Introduction

Underground mines are a main source of minerals. Growing demand for metals as a result of modern lifestyles and the industrial development of recent decades has

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focused our attention on the factors affecting the extraction of minerals. One of the most important factors is unscheduled downtime of the machines used in the extraction of ore. Lost production due to downtime will obviously increase the production costs (Roman and Daneshmend, 2000). A mine production system consists of many subsystems. To make the system both profitable and practical, the optimisation of each subsystem in relation with other subsystems should be considered (Barabady and Kumar, 2008). To achieve this aim, reliability and maintainability analysis for each subsystem in mine production system should be performed. Since the mid-1980s, reliability analysis techniques have been essential tools in automatic mining systems (Blischke and Murthy, 2003; Barabady and Kumar, 2008).

A drilling machine is very important to the extraction process. Drilling is the process of making holes in the mining room face. From an economic viewpoint, the drilling machine dominates a mine's production rate, since drilling is the first process of a typical mining cycle. Economic competition has pushed mining companies to achieve higher production rates by enhancing techniques of drilling and blasting and increasing mechanisation and automation. A significant cost issue is the maintenance of underground mobile machines: 30-65 per cent of a mine's total operation costs typically come from maintenance (Cutifani *et al.*, 1996; Gustafson *et al.*, 2013). Maintenance costs include the cost of planned and unplanned maintenance.

Historical data over the period of one year from an underground mine in Sweden show that more than 15 per cent of unplanned downtime of mobile machines is related to the drilling machine. Since the drilling machine is key to production, it is important to find solutions for machine problems and reduce downtime.

This study performs downtime analysis of drilling machine to identify which components and what type of problems (maintainability problems and/or reliability problems) contribute to downtime, and to determine which strategies, designs for maintainability and/or designs for reliability should be applied to reduce it. To better understand the downtime of the drilling machine, we conducted an analysis of the historical data for three machines of the same model used in one Swedish mine and for one machine used in another mine, using jack-knife diagrams with confidence intervals. The results of a study of downtime with or without confidence intervals for only one machine used in only one mine may not give a clear picture of the overall behaviour of the machine's components. Thus, it will prevent the designers to give good suggestions to improve the reliability and/or maintainability of the machine. To overcome this shortcoming, a comparison study and an analysis of the downtime by using jack-knife diagrams with confidence intervals for one machine used in mine X and three machines same model used in mine Y was conducted during this study. The reason of using data for one machine, which used in mine X, is that this mine has only one machine of the same model of the machines that used in mine Y. This diagram was used in order to overcome the shortcomings of using Pareto diagrams in maintenance engineering applications (Knights, 2001).

A jack-knife diagram has one shortcoming; it presents downtime as a single value (point estimated), and because of involved uncertainties it has been considered insufficient (Altman *et al.*, 2000; Curran-Everett and Benos, 2004; Wijaya *et al.*, 2012). System designers and users have a tendency to be risk-averse regarding downtime. They prefer a design with a slightly higher estimated downtime (lower reliability) if the estimated value is known to be accurate (as characterised by the upper limit of a confidence interval of the downtime) rather than a design with possible inaccuracies in point estimation; therefore, it is important to consider a confidence interval for system downtime (Colt, 1997).

1.1 Literature review

Many researchers 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. Kumar *et al.* (1992) performed reliability analysis on the power transmission cables of electric mine loaders in Sweden. Kumar and Klefsjö (1992) analysed the maintenance data of one subsystem (hydraulic system) of a fleet of six LHD machines divided into three independent groups at Kiruna mine.

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. 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. Wijaya *et al.* (2012) developed a method for visualising downtime by using a jack-knife diagram; they applied the method on a scaling machine at a mine in Sweden. Gustafson *et al.* (2013) used a fault tree analysis to analyse the idle times of automated LHD machines at a Swedish underground mine. Hoseinie *et al.* (2012) performed reliability modelling of the drum Shearer machine used at Taba's coal mine in the central desert of Iran. They analysed the failure rate of the machine's subsystems.

As the literature review shows, there are many reliability and maintainability studies of underground mining equipment but none of these has looked at drilling machines. Given the importance of underground mining mobile equipment for production, as well as the complexity of the equipment and the harsh mining environment, reliability analysis of the drilling machine must meet rigorous requirements. This study is based on data from several drilling machines working in different mines. In these mines the working environment, ore properties and operators are different.

The aims of this study are as follows:

(1) to analyse the reliability and downtime of several drilling machines to determine what kind of problems affect their downtime;

(2) to specify which strategies, design for maintainability and/or design for reliability (DFR) should be applied to reduce the drilling machines downtime; and

(3) to suggest improvement for the components that most contribute to the machines downtime.

2. Drilling machine and data collection

All drilling machines for mining applications are composed of similar operational design units, such as 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. A typical example of a drilling machine and its components are presented in Figure 1.

Drilling machines manufactured by different companies have different technical characteristics, e.g. capacity and power. Based on the operation manuals, field observations and maintenance reports from the collaborating mines, in this study the drilling machine is considered a system divided into several components and connected in series configuration; if any component fails, the operator will stop the machine to maintain it. Thus, all machine components work simultaneously to achieve

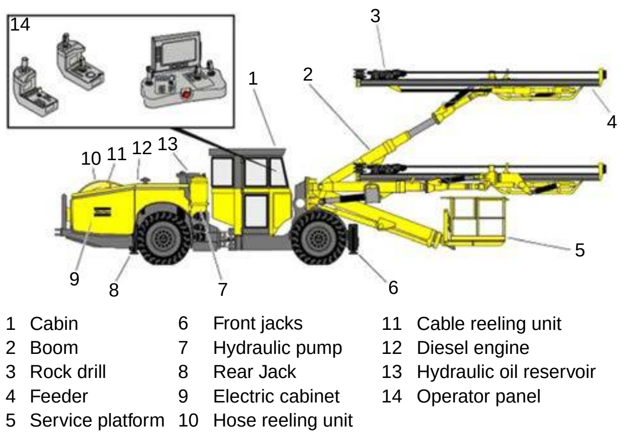


Figure 1. A typical example of a drilling machine

the desired function. Table I shows the critical components for each machine mentioned in this study.

The dimensions of the drilling machine are: length 14.5-16.6 m; width 2.5 m; width of rig with side platforms 2.9 m; height of rig with cabin 3.15 m; weight 26-33 tonnes. It has four retractable stabilizer legs and an articulated four-wheel drive chassis. It can be operated by a water cooled turbocharged diesel engine with 120 kW at 2,300 rpm or by electric power with a capacity of 158 kW.

3. Reliability and downtime analysis

The failure data used in this study were collected over two years for four drilling machines operated in two different underground mines in Sweden. The Maximo computerised maintenance management system (CMMS) is the main source of the failure data. In CMMS, the failure data are recorded based on calendar time. Since drilling is not a continuous process, the time between failures is estimated by considering the utilisation of each machine. In this study, we test and validate the failure and repair data after collection. We test for trends using the Laplace trend test; we also test for serial correlation (Ansell and Phillips, 1994). When these tests are used, depending on the results, classical statistical techniques for reliability modelling may be appropriate (Ascher and Feingold, 1984; Kumar and Klefsjö, 1992; Modarres, 2006; Birolini, 2007; Louit *et al.*, 2009; Ghosh and Majumdar, 2011). The Kolmogorov-Smirnov (K-S) test is

Mine X				Mine Y			
Machine 1		Machine 2		Machine 3		Machine 4	
Component	Sym.	Component	Sym.	Component	Sym.	Component	Sym.
Rock drill	A1	Rock drill	A2	Rock drill	A3	Rock drill	A4
Feeder	B1	Feeder	B2	Feeder	B3	Feeder	B4
Hoses	C1	Hoses	C2	Hoses	C3	Hoses	C4
		Accumulators	D2	Accumulators	D3	Accumulators	D4
		Boom	E2	Boom	E3	Boom	E4
		Cables	F2	Cables	F3	Cables	F4
Steering system	G1			Steering system	G3	Steering system	G4
Cylinders	H1			Cylinders	H3	Cylinders	H4

Table I. Critical components for each machine classically used for the selection and validation of the probability distribution models (for further information, refer to Louit *et al.*, 2009). In this study, we conduct all component analysis based on the black box approach.

To estimate the interval of downtimes, we assume that the failure times have a Weibull distribution and the repair times have a lognormal distribution. In addition to its flexibility, the Weibull distribution gives a reasonably accurate failure analysis even with a small sample size (Masters *et al.*, 1992; Abernethy, 2000). The shape and scale parameters of the Weibull distribution are determined by using the maximum likelihood estimation method. Lognormal distribution is generally used to model repair times (Rausand and Hoyland, 2004; Schroeder and Gibson, 2010). The long tail to the right of lognormal distribution provides the best fitting representation of the repair situation. Most repairs are accomplished in a small period of time, but in certain cases, repairs can take a much longer time (Wijaya *et al.*, 2012). The Weibull distribution has a probability density function given by:

$$g(y) = \frac{\beta}{\eta}\left(\frac{y}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{y}{\eta}\right)^{\beta}\right], \quad y>0 \tag{1}$$

where β and η are the shape and the scale parameters of the Weibull distribution, respectively. The expected mean time between failures (MTBF) is given as:

$$MTBF = \mu_y = \eta\Gamma\left(\frac{1}{\beta}+1\right) \tag{2}$$

Lognormal distribution has a probability density function given by:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{\ln(x)-\mu}{\sigma}\right)^2\right], \quad x>0 \tag{3}$$

where σ and μ are the standard deviation and the mean of the variable's natural logarithm, respectively. The expected mean time to repair (MTTR) is given as:

$$MTTR = \mu_x = \exp\left(\mu + \frac{\sigma^2}{2}\right) \tag{4}$$

The confidence interval of the downtime is determined according to the following equations:

$$MTTR = \frac{DT}{m} \tag{5}$$

$$MTBF = \frac{UT}{m} \tag{6}$$

$$\frac{DT}{UT} = \frac{MTTR}{MTBF} \tag{7}$$

where DT is the downtime, m is the number of failures and UT is the uptime. Thus, the downtime can be formulated as (Wijaya *et al.*, 2012):

$$DT = \frac{\mu_x}{\mu_y} UT \tag{8}$$

The confidence interval of the estimated downtime can be solved by finding a confidence interval for μ_x/μ_y. In this study, the exact method (Masters *et al.*, 1992) is implemented to estimate the confidence interval of μ_x/μ_y (for more clarification of the method to estimate the interval of the downtime, see Wijaya *et al.*, 2012). All tests are conducted using the Minitab, Matlab and Easy Fit software; the significance level α used in all tests is 0.05.

4. Methodology

A simple yet important graphical method to visualise downtime is the jack-knife diagram (Knights, 2001). In this diagram, the failure data are presented as a log-log graph. The graph shows log number of failures (vertical axis) and log repair time (horizontal axis). The curves of constant downtime appear as straight lines with a uniform and constant gradient (Knights, 2001). This study uses the jack-knife diagram with the downtime confidence interval to analyse the downtime of the components of the drilling machine. Three equations are used to establish the confidence log-log plot. The estimation points are the mean, lower limit and upper limit of the downtime. The value of these points can be estimated from the following equations (Wijaya *et al.*, 2012):

$$DT_M = \left[\frac{\exp\left(\mu + \frac{\sigma^2}{2}\right)}{\eta \Gamma\left(\frac{1}{\beta} + 1\right)} \right] \times UT \tag{9}$$

$$DT_{LL} = \left[a \times \frac{\exp\left(\frac{\sigma^2}{2}\right) G}{\Gamma\left(\frac{1}{\beta} + 1\right) 2\eta^{1-\beta} \sum_{i=1}^{m} y_i^{\beta}} \right] \times UT \tag{10}$$

$$DT_{UL} = \left[b \times \frac{\exp\left(\frac{\sigma^2}{2}\right) G}{\Gamma\left(\frac{1}{\beta} + 1\right) 2\eta^{1-\beta} \sum_{i=1}^{m} y_i^{\beta}} \right] \times UT \tag{11}$$

where DT_M is mean downtime, DT_{LL} is a lower limit of the downtime, a is a constant for the lower limit, G is a geometric mean of the lognormal distribution, y is time between failures, DT_{UL} is an upper limit of the downtime and b is a constant for the upper limit.

The next step is the determination of coordinates of the three previous estimated points. For the DT_M, the abscissa is the MTTR, and the ordinate is determined as:

$$m_M = \frac{UT}{MTBF} \quad (12)$$

For the lower and upper limit of the downtime, the abscissa and the ordinate are determined as:

$$TTR_L = 10^{\left[\log\sqrt{DT_L} - \log\sqrt{DT_M} + \log(MTTR)\right]} \quad (13)$$

$$m_L = \frac{DT_L}{TTR_L} \quad (14)$$

where TTR_L is time to repair of the limit (upper or lower); DT_L is the downtime of the limit (upper or lower); $MTTR$ is mean time to repair; m_L is the number of failures of the limit (upper or lower). For more information on derivation of the abscissa, the lower and upper limits of downtime refer to Wijaya *et al.* (2012).

To estimate the interval of the downtime, the three estimated points are connected by a straight line (Figure 2).

5. Results and discussion

The present study only considers corrective maintenance. It assumes that the failure times follow a Weibull distribution and the repair times follow a lognormal distribution; therefore, the *iid* assumption is validated before analysis. The maximum likelihood estimation method is used to estimate the corresponding parameters using Minitab software. K-S test is used to validate the distributions using Easy Fit software.

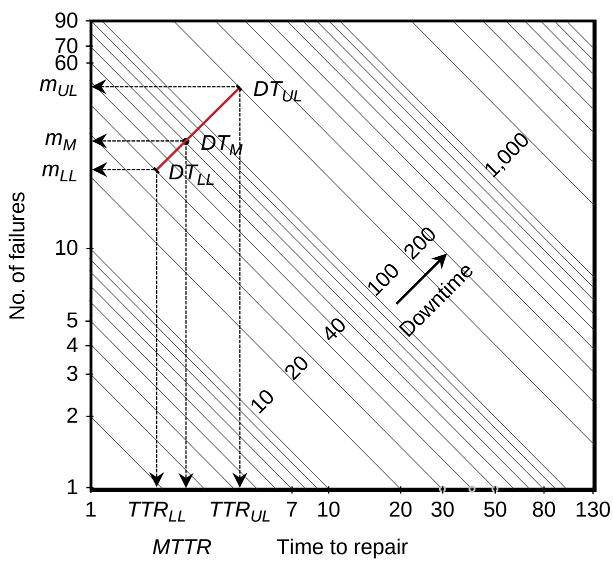


Figure 2.
Log-log plot of downtime confidence interval

Parameters of the distributions are determined the lower bound, mean and upper bound for a confidence interval of 95 per cent. For the failure data, β_{low} and β_{upp} are the estimates of the lower and upper limits, respectively, of the maximum likelihood estimate of shape parameter β, denoted by β_{est}. η_{low} and η_{upp} are the estimates of the lower and upper limits, respectively, of the maximum likelihood estimate of scale parameter η, denoted by η_{est}. $MTBF_{low}$ and $MTBF_{upp}$ are the estimates of the lower and upper limits, respectively, of the maximum likelihood estimate of the MTBF, denoted by $MTBF_{est}$. For the repair data, μ_{low} and μ_{upp} are the estimates of the lower and upper limits, respectively, of the maximum likelihood estimate of the mean parameter μ of the lognormal distribution, denoted by μ_{est}. σ_{low} and σ_{upp} are the estimates of the lower and upper limits, respectively, of the maximum likelihood estimate of the standard deviation parameter σ of the lognormal distribution, denoted by σ_{est}. $MTTR_{low}$ and $MTTR_{upp}$ are the estimates of the lower and upper limits, respectively, of the maximum likelihood estimate of the MTTR, denoted by $MTTR_{est}$.

Tables II-V show the data analysis of the critical components of four drilling machines working in two different mines in Sweden.

We compare the machines' downtime using a jack-knife diagram with a confidence interval. Using Equations (9-11), we determine three downtime estimation points, DT_M, DT_{LL} and DT_{UL}. The study uses theoretical production hours for one year as uptime. When the data were collected for this study, each mine averaged about 16.5 working hours per day, or approximately 115 hours per week. By fitting lognormal distribution for preventive maintenance (PM) data (service data) to all machines, we find that mean time to service averages 6.7 hours. Since PM is scheduled for every week, the theoretical service time for 49 working weeks for one year is calculated as approximately 330 hours. Consequently, the stoppage for PM is three weeks per year; hence, each mine is worked for 46 weeks per year. We can conclude that each mine has approximately 5,300 production hours per year. The coordinates of the three downtime estimation points are determined by using Equations (4), (12-14). Tables VI-IX shows the values of the three estimation points and their coordinates.

We make four types of comparisons of the downtime of the machines' components. Type 1 is a comparison of six components on three machines used only in mine Y. Type 2 is a comparison of three components on four machines (1, 2, 3 and 4) used in both mines. Type 3 is a comparison of two components on three machines (1, 3 and 4) used in both mines. Type 4 compares one component on two machines (1 and 2) used in both mines. Figures 3-9 are visualisations of these four types of comparisons.

Since the number of failures and repair time are noted manually, we expect these data have some errors. Based on interviews with several maintenance persons who work in the mines collaborating in this study, we conclude that 80 per cent of the data does not include documentation errors. With this in mind, we define a ratio R, whereby $R =$ maximum mean downtime/minimum mean downtime, and determine the following limits:

(1) no significant differences; $1 \leqslant R \leqslant 1.2$;

(2) indicated differences; $1.2 < R \leqslant 1.4$; and

(3) significant differences; $R > 1.4$.

Figure 3 shows for a given uptime of 5,300 hours, there is a significant difference between E2, E3 and E4 (boom), as $R = 3.5$. Also there is a significant difference between A2, A3 and A4 (rock drill), as $R = 1.7$. But there is no significant

Table II.
Summary for machine 1, mine X

	Component	m	β_{low}	β_{est}	β_{upp}	η_{low}	η_{est}	η_{upp}	$MTBF_{low}$	$MTBF_{est}$	$MTBF_{upp}$
			Weibull parameters				Time to failure (95% normal CI)				
(a) Failure data[a]											
A1	Rock drill	21	0.68	0.94	1.3	62.8	102.6	167.6	66.2	105.1	166.8
B1	Feeder	7	0.76	1.47	2.85	186.5	330.8	586.7	172.4	299.3	519.6
C1	Hoses	61	0.68	0.82	0.99	23.9	33.3	46.4	27.1	37.0	50.6
G1	Steering system	26	0.71	0.95	1.29	54.5	84.0	129.5	56.9	85.6	128.8
H1	Cylinders	5	1.48	3.78	9.62	262.8	343.3	448.4	233.4	310.2	412.2
I1	Hydraulics	5	0.74	1.55	3.23	186.0	363.5	710.5	170.9	326.8	624.8
J1	Fuel system	5	0.61	1.29	2.71	138.4	309.7	692.8	132.9	286.3	616.5
			Lognormal parameters				Time to repair (95% normal CI)				
	Component	m	σ_{low}	σ_{est}	σ_{upp}	μ_{low}	μ_{est}	μ_{upp}	$MTTR_{low}$	$MTTR_{est}$	$MTTR_{upp}$
(b) Repair data[b]											
A1	Rock drill	21	0.42	0.57	0.77	0.09	0.33	0.58	1.2	1.6	2.1
B1	Feeder	7	0.44	0.74	1.2	0.17	0.72	1.27	1.4	2.7	5.0
C1	Hoses	61	0.41	0.49	0.59	0.13	0.25	0.38	1.2	1.4	1.6
G1	Steering system	26	0.59	0.78	1.02	0.44	0.74	1.04	2.0	2.8	4.0
H1	Cylinders	5	0.19	0.36	0.67	0.20	0.52	0.83	1.2	1.7	2.4
I1	Hydraulics	5	0.38	0.72	1.34	0.55	0.08	0.71	0.6	1.4	2.8
J1	Fuel system	5	0.14	0.27	0.51	0.10	0.13	0.38	0.9	1.1	1.5

Notes: m is the number of failures. [a]η and MTBF are given in units of hours; [b]MTTR is given in units of hours

Table III. Summary for machine 2, mine Y

	Component	m	β_{low}	β_{est}	β_{upp}	η_{low}	η_{est}	η_{upp}	$MTBF_{low}$	$MTBF_{est}$	$MTBF_{upp}$
			Weibull parameters				Time to failure (95% normal CI)				
(a) Failure data[a]											
A2	Rock drill	39	0.77	0.97	1.24	47.7	69.0	99.9	49.1	69.7	98.7
B2	Feeder	37	0.65	0.83	1.07	36.0	55.4	85.4	40.5	60.9	91.6
C2	Hoses	124	0.80	0.92	1.06	16.7	20.7	25.6	17.6	21.5	26.3
D2	Accumulators	10	0.70	1.22	2.13	156.1	272.7	476.3	149.6	254.9	434.4
E2	Boom	19	0.70	1.04	1.54	87.5	146.2	244.5	88.5	143.8	233.8
F2	Cables	7	0.79	1.50	2.83	298.1	555.1	1033.8	275.0	501.0	912.7
I2	Hydraulics	5	0.73	1.51	3.12	143.8	286.6	571.1	132.9	258.4	502.6
J2	Control panel	19	0.86	1.30	1.95	87.5	131.8	198.7	82.3	121.7	180.1
K2	Water cooler	8	0.45	0.84	1.54	121.6	332.2	907.6	140.4	363.1	938.6
L2	Valves[a]	23	0.67	0.93	1.3	67.9	109.9	178.0	71.7	113.2	178.5
M2	Manual valves	16	0.78	1.18	1.79	113.5	180.9	288.1	109.5	170.5	265.4
N2	Movement device	6	0.61	1.28	2.65	211.2	434.6	893.9	202.3	402.6	801.2

	Component	m	σ_{low}	σ_{est}	σ_{upp}	μ_{low}	μ_{est}	μ_{upp}	$MTTR_{low}$	$MTTR_{est}$	$MTTR_{upp}$
			Lognormal parameters				Time to repair (95% normal CI)				
(b) Repair data[b]											
A2	Rock drill	39	0.41	0.52	0.65	0.27	0.44	0.60	1.5	1.7	2.1
B2	Feeder	37	0.46	0.58	0.73	0.72	0.91	1.10	2.4	2.9	3.6
C2	Hoses	124	0.56	0.64	0.72	0.48	0.59	0.70	1.9	2.2	2.5
D2	Accumulators	10	0.29	0.45	0.71	0.13	0.15	0.43	0.9	1.2	1.7
E2	Boom	19	0.51	0.71	0.97	0.75	1.07	1.39	2.6	3.7	5.4
F2	Cables	7	0.36	0.62	1.05	0.24	0.70	1.17	1.4	2.4	4.0
I2	Hydraulics	5	0.23	0.43	0.81	0.16	0.21	0.60	0.9	1.3	2.0
J2	Control panel	19	0.37	0.51	0.71	0.10	0.34	0.57	1.2	1.6	2.0
K2	Water cooler	8	0.52	0.85	1.39	0.007	0.58	1.17	1.2	2.5	5.1
L2	Valves	23	0.51	0.68	0.91	0.17	0.45	0.73	1.4	1.9	2.7
M2	Manual valves	16	0.42	0.60	0.85	0.07	0.36	0.66	1.2	1.7	2.4
N2	Movement device	6	0.37	0.66	1.17	0.36	0.89	1.42	1.6	3.0	5.5

Notes: m is the number of failures. [a]η and MTBF are given in units of hours; [b]MTTR is given in units of hours

Table IV.
Summary for machine 3, mine Y

	Component	m	β_{low}	β_{est}	β_{upp}	η_{low}	η_{est}	η_{upp}	$MTBF_{low}$	$MTBF_{est}$	$MTBF_{upp}$
			Weibull parameters				Time to failure (95% normal CI)				
(a) *Failure data*[a]											
A3	Rock drill	38	0.62	0.78	0.99	32.1	50.0	77.7	37.8	57.3	87.0
B3	Feeder	54	0.66	0.81	1.01	29.7	42.4	60.7	33.6	47.3	66.4
C3	Hoses	45	0.83	1.05	1.33	43.2	58.1	78.0	42.9	56.8	75.2
D3	Accumulators	6	0.66	1.39	2.94	169.4	325.5	625.5	157.9	296.7	557.5
E3	Boom	8	1.14	1.93	3.28	266.7	400.9	602.5	237.7	355.5	531.9
F3	Cables	7	0.57	1.08	2.04	182.9	399.6	873.0	146.2	387.6	811.9
G3	Steering system	24	0.91	1.28	1.79	85.0	120.8	171.8	80.0	111.9	156.7
H3	Cylinders	14	0.56	0.86	1.33	90.2	180.0	359.0	100.7	193.2	370.6
			Lognormal parameters				Time to repair (95% normal CI)				
	Component	m	σ_{low}	σ_{est}	σ_{upp}	μ_{low}	μ_{est}	μ_{upp}	$MTTR_{low}$	$MTTR_{est}$	$MTTR_{upp}$
(b) *Repair data*[b]											
A3	Rock drill	38	0.63	0.79	0.99	0.36	0.62	0.87	1.9	2.5	3.4
B3	Feeder	54	0.56	0.68	0.82	0.61	0.79	0.97	2.2	2.7	3.4
C3	Hoses	45	0.48	0.60	0.73	0.31	0.49	0.66	1.6	1.9	2.3
D3	Accumulators	6	0.27	0.47	0.83	0.26	0.11	0.49	0.8	1.2	1.8
E3	Boom	8	0.38	0.62	1.02	0.33	0.77	1.20	1.6	2.6	4.2
F3	Cables	7	0.24	0.41	0.70	0.14	0.45	0.76	1.2	1.7	2.3
G3	Steering system	24	0.45	0.60	0.79	0.37	0.61	0.85	1.7	2.2	2.8
H3	Cylinders	14	0.28	0.42	0.62	0.41	0.64	0.87	1.6	2.0	2.6

Notes: m is the number of failures. [a]η and MTBF are given in units of hours; [b]MTTR is given in units of hours

Table V. Summary for machine 4, mine Y

							Time to failure (95% normal CI)				
			Weibull parameters								
	Component	m	β_{low}	β_{est}	β_{upp}	η_{low}	η_{est}	η_{upp}	$MTBF_{low}$	$MTBF_{est}$	$MTBF_{upp}$
(a) Failure data[a]											
A4	Rock drill	46	0.83	1.05	1.33	45.0	60.6	81.7	44.7	59.4	78.9
B4	Feeder	49	0.88	1.10	1.38	43.9	57.9	76.3	42.9	55.8	72.5
C4	Hoses	78	0.81	0.96	1.15	28.0	35.9	46.0	28.8	36.4	46.0
D4	Accumulators	6	0.68	1.48	3.19	270.1	502.0	933.1	249.6	453.8	825.0
E4	Boom	15	0.62	0.93	1.41	100.6	181.7	328.1	107.0	187.0	326.7
F4	Cables	5	0.58	1.27	2.79	305.7	685.8	1,538.4	293.8	635.5	1,374.6
G4	Steering system	15	0.90	1.34	2.00	135.2	203.8	307.2	126.1	187.0	277.1
H4	Cylinders	6	0.84	1.81	3.88	255.5	452.8	802.4	229.5	402.5	705.9
J4	Generator	6	0.41	0.99	2.40	108.0	299.8	831.8	112.0	299.9	802.8
K4	Pumps	5	0.69	1.54	3.41	259.2	507.3	992.9	238.6	456.6	873.7
							Time to repair (95% normal CI)				
			Lognormal parameters								
	Component	m	σ_{low}	σ_{est}	σ_{upp}	μ_{low}	μ_{est}	μ_{upp}	$MTTR_{low}$	$MTTR_{est}$	$MTTR_{upp}$
(b) Repair data[b]											
A4	Rock drill	46	0.49	0.60	0.74	0.28	0.45	0.63	1.5	1.8	2.2
B4	Feeder	49	0.60	0.73	0.89	0.42	0.62	0.83	1.9	2.4	3.0
C4	Hoses	78	0.45	0.53	0.62	0.29	0.41	0.52	1.5	1.7	1.9
D4	Accumulators	6	0.40	0.71	1.25	0.15	0.41	0.98	1.0	1.9	3.7
E4	Boom	15	0.51	0.74	1.06	0.28	0.66	1.04	0.5	2.5	3.9
F4	Cables	5	0.33	0.62	1.16	0.13	0.68	1.22	1.3	2.4	4.3
G4	Steering system	15	0.31	0.44	0.63	0.19	0.42	0.65	1.3	1.6	2.1
H4	Cylinders	6	0.27	0.47	0.83	0.19	0.57	0.95	1.3	1.9	2.9
J4	Generator	6	0.44	0.78	1.38	0.08	0.71	1.34	1.3	2.7	5.6
K4	Pumps	5	0.35	0.66	1.23	0.36	0.94	1.52	1.6	3.2	6.1

Notes: m is the number of failures. [a]η and MTBF are given in units of hours; [b]MTTR is given in units of hours

difference between D2, D3 and D4 (accumulators), as $R=1.2$ in this particular case. Moreover, component A3 in machine 3 has more downtime than the similar component used in machines 2 and 4. Similarly, component E2 in machine 2 has more downtime than components E3 and E4. Figure 3 shows there are notable differences in the downtime of most of the studied components for all machines used in mine Y.

Table VI. Three estimation points of the downtime and their coordinates for machine 1, mine X

	Component	Downtime			Repair time/failure			No. of failures		
		DT_{LL}	DT_M	DT_{UL}	TTR_{LL}	MTTR	TTR_{UL}	m_{LL}	m_M	m_{UL}
A1	Rock drill	55.5	83.0	127.8	1.3	1.6	2.0	41.2	50.4	62.5
B1	Feeder	23.0	48.2	111.4	1.8	2.7	4.1	12.2	17.7	26.9
C1	Hoses	171.7	209.2	274.8	1.3	1.4	1.6	129.5	142.9	163.8
G1	Steering system	120.3	179.2	273.0	2.3	2.8	3.5	50.7	61.9	76.4
H1	Cylinders	14.5	30.7	74.3	1.2	1.7	2.7	11.7	17.0	26.5
I1	Hydraulics	9.7	22.8	62.1	0.9	1.4	2.3	10.5	16.2	26.7
J1	Fuel system	10.6	22.0	52.1	0.8	1.1	1.8	12.8	18.5	28.4

Notes: DT_M, DT_{LL}, DT_{UL}, MTTR, TTR_{LL} and TTR_{UL} are given in units of hours

Table VII. Three estimation points of the downtime and their coordinates for machine 2, mine Y

	Component	Downtime			Repair time/failure			No. of failures		
		DT_{LL}	DT_M	DT_{UL}	TTR_{LL}	MTTR	TTR_{UL}	m_{LL}	m_M	m_{UL}
A2	Rock drill	117.0	136.0	213.4	1.6	1.7	2.2	70.5	76.0	95.2
B2	Feeder	208.3	259.4	390.5	2.6	2.9	3.6	77.9	86.9	106.6
C2	Hoses	510.6	547.9	726.3	2.1	2.2	2.5	237.6	246.2	283.5
D2	Accumulators	15.4	26.8	49.5	0.9	1.2	1.7	15.7	20.7	28.2
E2	Boom	106.8	139.5	271.8	3.3	3.7	5.2	32.2	36.8	51.4
F2	Cables	15.6	26.1	70.3	1.9	2.4	4.0	8.1	10.5	17.3
I2	Hydraulics	13.1	28.1	69.6	0.9	1.3	2.1	14.0	20.5	32.2
J2	Control panal	55.6	69.9	131.6	1.4	1.6	2.2	38.7	43.5	59.6
K2	Water cooler	21.2	37.7	101.7	1.9	2.5	4.2	10.9	14.5	23.9
L2	Valves	65.4	93.6	151.5	1.6	1.9	2.5	39.1	46.8	59.5
M2	Manual valves	36.3	53.9	95.9	1.4	1.7	2.3	25.4	31.0	41.4
N2	Movement device	18.7	40.2	98.0	2.0	3.0	4.7	8.9	13.1	20.5

Notes: DT_M, DT_{LL}, DT_{UL}, MTTR, TTR_{LL} and TTR_{UL} are given in units of hours

Table VIII. Three estimation points of the downtime and their coordinates for machine 3, mine Y

	Component	Downtime			Repair time/failure			No. of failures		
		DT_{LL}	DT_M	DT_{UL}	TTR_{LL}	MTTR	TTR_{UL}	m_{LL}	m_M	m_{UL}
A3	Rock drill	174.1	236.5	345.5	2.1	2.5	3.0	79.2	92.3	111.6
B3	Feeder	254.2	312.8	437.5	2.5	2.7	3.3	100.9	111.9	132.4
C3	Hoses	137.9	182.5	245.0	1.7	1.9	2.2	80.9	93.1	107.9
D3	Accumulators	11.0	22.4	51.2	0.8	1.2	1.8	12.5	17.8	26.9
E3	Boom	20.3	39.2	81.6	1.8	2.6	3.7	10.7	14.9	21.5
F3	Cables	12.3	23.4	48.9	1.2	1.7	2.4	9.8	13.6	19.7
G3	Steering system	78.5	105.0	172.9	1.9	2.2	2.8	40.9	47.3	60.7
H3	Cylinders	44.7	67.3	123.8	2.0	2.4	3.3	22.3	27.4	37.1

Notes: DT_M, DT_{LL}, DT_{UL}, MTTR, TTR_{LL} and TTR_{UL} are given in units of hours

	Component	Downtime			Repair time/failure			No. of failures		
		DT_{LL}	DT_{M}	DT_{UL}	TTR_{LL}	MTTR	TTR_{UL}	m_{LL}	m_{M}	m_{UL}
A4	Rock drill	134.0	169.1	237.2	1.6	1.8	2.2	79.3	89.1	105.5
B4	Feeder	183.8	234.4	330.1	2.1	2.4	2.9	84.1	94.9	112.7
C4	Hoses	213.9	253.1	326.9	1.5	1.7	1.9	133.7	145.4	165.3
D4	Accumulators	10.4	22.8	56.8	1.3	1.9	3.0	7.8	11.6	18.4
E4	Boom	43.5	72.5	126.5	1.9	2.5	3.3	21.9	28.3	37.4
F4	Cables	8.8	20.0	53.3	1.5	2.4	3.9	5.5	8.3	13.6
G4	Steering system	30.4	47.8	77.9	1.3	1.6	2.1	22.6	28.3	36.1
H4	Cylinders	16.1	26.2	74.9	1.5	1.9	3.3	10.3	13.1	22.2
J4	Generator	27.3	49.0	157.3	2.0	2.7	4.9	13.1	17.6	31.6
K4	Pumps	16.1	37.2	101.0	2.1	3.2	5.2	7.6	11.6	19.1

Notes: DT_{M}, DT_{LL}, DT_{UL}, MTTR, TTR_{LL} and TTR_{UL} are given in units of hours

Table IX. Three estimation points of the downtime and their coordinates for machine 4, mine Y

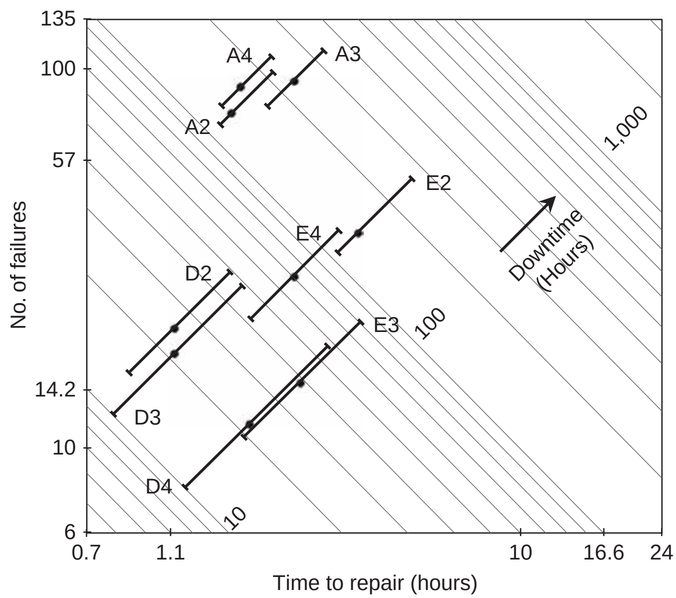


Figure 3. Confidence log-log plot comparison between three machines used in mine Y

When we interpret Figures 4-9 in the same way, we conclude the results of the ratio R for all machine components, as shown in Table X.

Table X it shows notable differences in the downtime of most investigated components of all machines used in both mines. For the machines used in the same mine, three out of six components have significant differences. For the machines used in different mines, five out of six components have significant differences.

Figure 4 indicates that the components C2 and B3 have higher downtime than the equivalent components in another machine used in the same mine.

Figure 5 and 6 illustrate that the components A1 and B1 used in machine 1 in mine X have less downtime than the same components used in the machines in mine Y. This may be due to the differences of the rock properties between the two mines. The geological strength index (GSI) of mine Y varies between 50 and 80

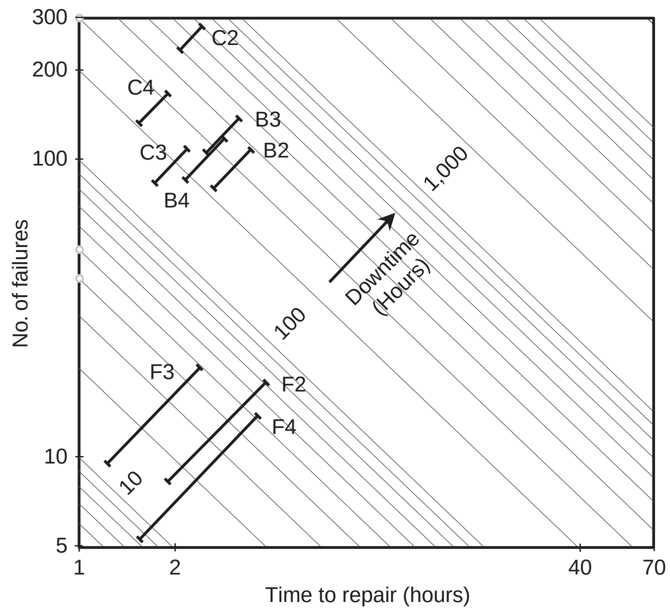


Figure 4.
Confidence log-log plot comparison between three machines used in mine Y

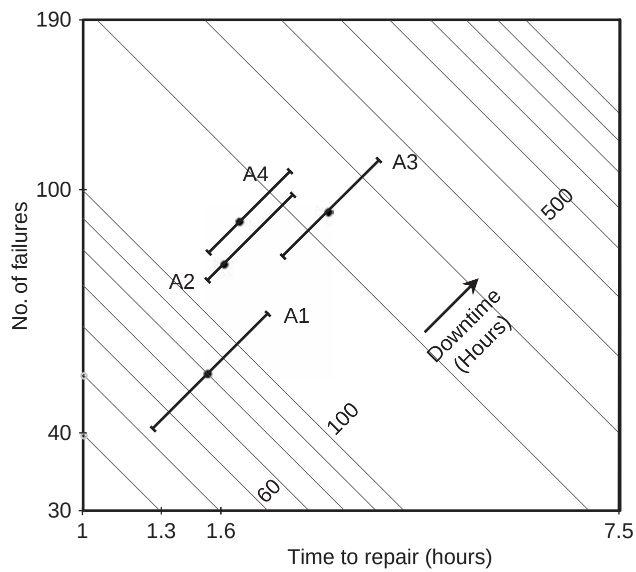
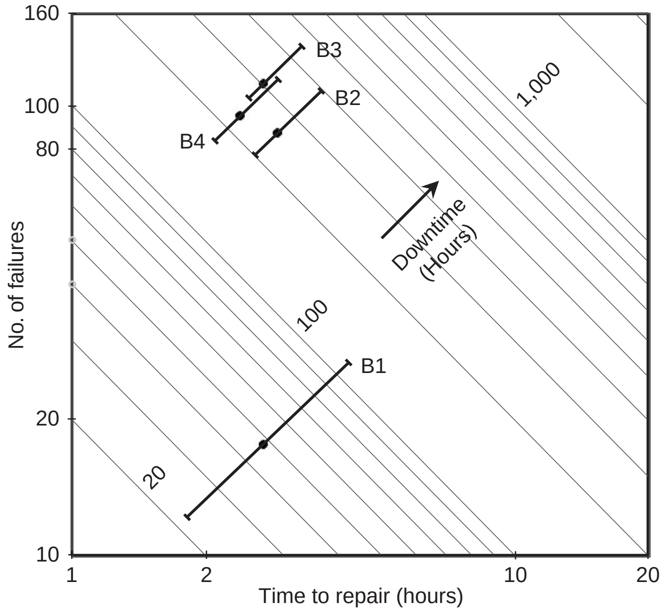


Figure 5.
Confidence log-log plot comparison between four machines used in both mines

Notes: A1 (rock drill) and B1 (feeder) are components used in machine 1 in mine X, while A2, A3 and A4 (rock drill), B2, B3, and B4 (feeder) are components used in machines 2, 3 and 4 in mine Y



Note: A1 (rock drill) and B1 (feeder) are components used in machine 1 in mine X, while A2, A3 and A4 (rock drill), B2, B3, and B4 (feeder) are components used in machines 2, 3 and 4 in mine Y

Figure 6.
Confidence log-log plot comparison between four machines used in both mines

(Edelbro, 2008) while the GSI of mine X varies between 30 and 50 (Sjöberg, 2003 as cited in Edelbro, 2008).

Figure 7 compares the downtime of component hoses C in four machines in different mines. Component C2 (hoses) has more downtime than the same components, C1, C3 and C4, used in the rest of the machines. A possible explanation is the difference in how the various machines were handling. However, further research is needed to confirm this explanation. Figures 5-7 clearly show that components B2 and C4 have approximately the same downtime (259 h and 253 h, respectively). Similarly, components A3 and B4 have approximately the same downtime (236 h and 234 h, respectively). In addition, at the upper limit of the downtime interval, components B4 and C4 have approximately the same downtime. The figures also show that at the lower limit of the downtime interval, components C4 and B2 have approximately the same downtime, as do components A3 and C1 and components C3 and A4.

Figure 8 compares two components used in machines 1, 3 and 4 in two different mines. The components G4 (steering system), H4 and H1 (cylinders) have approximately the same downtime at the upper limit of the downtime interval.

For comparison type four, Figure 9 shows no significant difference in the downtime of the component I (hydraulics) used in machines 1 and 2, as $R = 1.2$ in this particular case.

The order of the significant components has been prioritised by Wijaya *et al.* (2012), based on three scenarios: the mean estimation point of the downtime (the high-likelihood scenario), the upper limit estimation point of the downtime (the worst-case scenario) and the lower limit estimation point of the downtime (the best-case scenario).

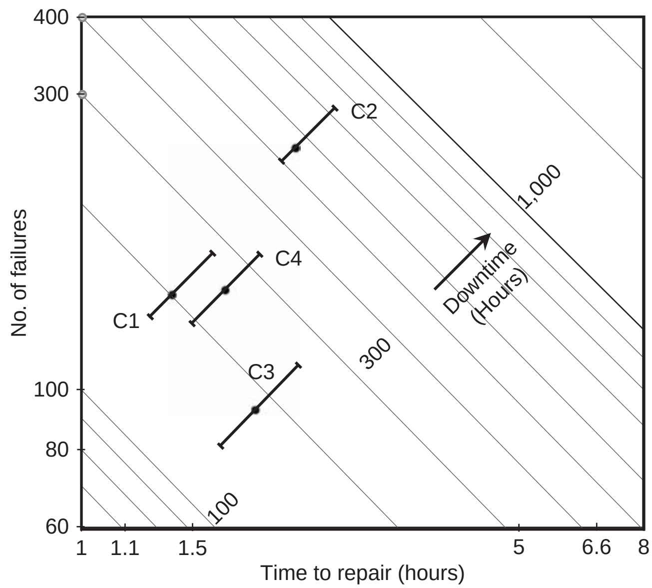
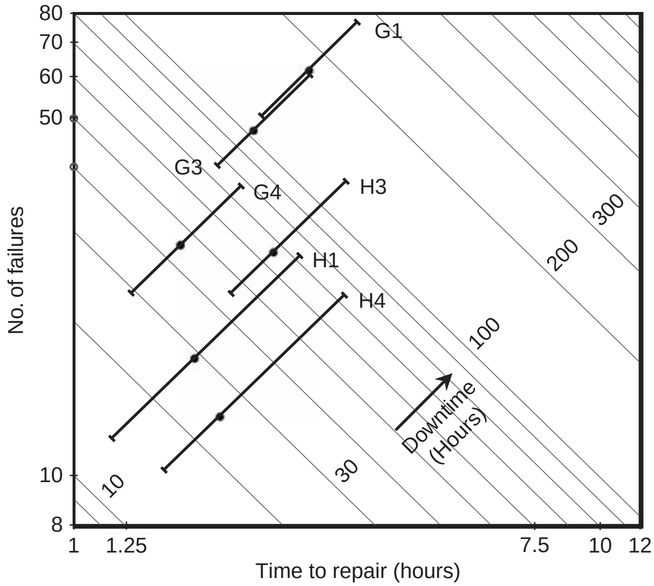


Figure 7.
Confidence log-log plot comparison between four machines used in both mines

Notes: C1 (hoses) is a component used in machine 1 in mine X, while C2, C3 and C4 (hoses), are components used in machines 2, 3, and 4 in mine Y. G1 (steering system) and H1 (cylinders) are components used in machine 1 in mine X; G3 and G4 (steering system), H3 and H4 (cylinders) are components used in machines 3 and 4 in mine Y

These three scenarios are important to decisions about certain activities in the mine, for instance, planning new operations and budgeting maintenance. Table XI illustrates the order of the significant components from the prioritisation of maintenance action point of view. During smooth operations, the component B4 (feeder) has a downtime of about 330 h more than component C4 (hoses) which has a downtime about 327 h. In the worst-case scenario of comparison type 1, component C4 should be given priority because it has a high number of breakdowns, combined with breakdowns of short duration; in comparison, component B4 has fewer breakdowns, combined with breakdowns of long duration; refer to Figure 4 and Table IX. This is important because a high frequency of breakdowns leads to a lower production rate as the machine needs more time to reach normal performance after each breakdown.

To cite another example, if the maintenance management department determines the highest acceptable amount of machine downtime at the component level, it is essential for the maintenance staff to know which components are likely to go beyond the acceptable limit. For example, if they decide that the highest acceptable amount of downtime is 350 hours per year for one component, in the worst-case scenario, we can observe in Figure 4 that components C2 (hoses on machine 2), B3 (feeder on machine 3) and B2 (feeder on machine 2) will exceed 350 hours of downtime. In this case, a good strategy may be to convince the manufacturing company to improve the lifetime of the components; another possibility is to increase the PM on these particular components. However, more research is needed on the topic.



Note: C1 (hoses) is a component used in machine 1 in mine X, while C2, C3 and C4 (hoses), are components used in machines 2, 3 and 4 in mine Y. G1 (steering system) and H1 (cylinders) are components used in machine 1 in mine X; G3 and G4 (steering system), H3 and H4 (cylinders) are components used in machines 3 and 4 in mine Y

Figure 8. Confidence log-log plot comparison between three machines used in both mines

5.1 Link between analysis and improvements

The following general method is suggested regarding the link between analysis and critical components improvement:

(1) collecting of maintenance and repair data;

(2) using confidence log-log diagram with reliability vs maintainability;

(3) identifying the most critical components (largest downtime);

(4) identifying the contribution of influencing factors (reliability and\or maintainability) for each of the critical components; and

(5) redesigning of the critical components with respect to the finding.

Using confidence log-log plots, we pinpoint reliability/maintainability problems in Figures 3-8. The plots show that at the upper limit of downtime ($DT_{UL} \geqslant 200$ hours) per year, components C (hoses), B (feeder), A (rock drill), E (boom) and G (steering system) have reliability problems, with a high number of failures and low levels of repair time. Thus, DFR strategy should be adopted to reduce their downtime.

5.2 Suggestions for critical components improvement

It has been concluded that the most common problem for all critical components is reliability problems. Therefore, this section will focus on suggestions on how to redesign the critical components to improve the reliability and reduce the machine's

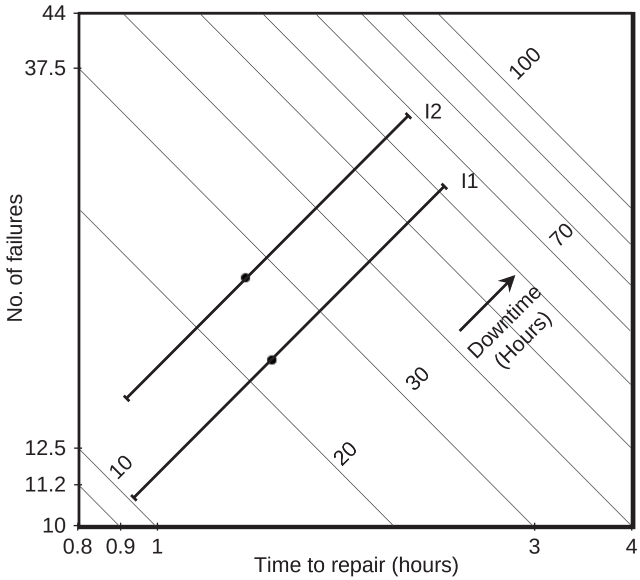


Figure 9.
Confidence log-log plot comparison between two machines used in both mines

Notes: I1 (hydraulics) is a component of machine 1 used in mine X; I2 (hydraulics) is a component in machine 2 in mine Y

Table X.
R ratio for machines components

Component	Symbol	Mine	Machine	Figure	*R*	Status
Rock drill	A2, A3, A4	Y	2, 3, 4	3	1.7	Significant differences
Boom	E2, E3, E4	Y	2, 3, 4	3	3.5	Significant differences
Accumulators	D2, D3, D4	Y	2, 3, 4	3	1.2	No significant differences
Hoses	C2, C3, C4	Y	2, 3, 4	4	3	Significant differences
Feeder	B2, B3, B4	Y	2, 3, 4	4	1.3	Indicated differences
Cables	F2, F3, F4	Y	2, 3, 4	4	1.3	Indicated differences
Rock drill	A1, A2, A3, A4	X, Y	1, 2, 3, 4	5	2.8	Significant differences
Feeder	B1, B2, B3, B4	X, Y	1, 2, 3, 4	6	6.5	Significant differences
Hoses	C1, C2, C3, C4	X, Y	1, 2, 3, 4	7	3	Significant differences
Steering system	G1, G3, G4	X, Y	1, 3, 4	8	3.7	Significant differences
Cylinders	H1, H3, H4	X, Y	1, 3, 4	8	2.5	Significant differences
Hydraulics	I1, I2	X, Y	1, 2	9	1.2	No significant differences

downtime. Discussions with maintenance personal reveal that the most of the failures in the feeder hoses are due to the mine's environment. For example, during drilling, the feeder hits the wall at different angles, especially when the feeder movement is restricted because of spatial limitations. To overcome this problem, the feeder could be equipped with an iron plate on both sides; the plate should be large enough to prevent hoses from being scratched and to prevent nipples at the necks from being broken (Plates 1-2 and Figure 10).

Another problem in the feeder is the pull rope breaking. This happens for two reasons. First, the pull rope relaxes with usage; it then hangs over the edge of the cradle plate when the plate moves forward and back on the slide bar (see Plates 3 and 4).

Type 1, mine Y three machines				Type 2, mine X and Y four machines				Type 3, mine X and Y three machines				Type 4, mine X and Y two machines			
	Scenario				Scenario				Scenario				Scenario		
Order	1	2	3	Order	1	2	3	Order	1	2	3	Order	1	2	3
1	C2	C2	C2	1	C2	C2	C2	1	G1	G1	G1	1	I2	I2	I2
2	B3	B3	B3	2	B3	B3	B3	2	G3	G3	G3	2	I1	I1	I1
3	B2	B2	C4	3	B2	B2	C4	3	H3	H3	H3				
4	C4	A3	B2	4	C4	A3	B2	4	G4	G4	G4				
5	A3	B4	B4	5	A3	B4	B4	5	H1	H4	H4				
6	B4	C4	A3	6	B4	C4	A3	6	H4	H1	H1				
7	C3	E2	C3	7	C1	C1	C1								
8	A4	C3	A4	8	C3	C3	C3								
9	E2	A4	A2	9	A4	A4	A4								
10	A2	A2	E2	10	A2	A2	A2								
11	E4	E4	E4	11	A1	A1	A1								
12	E3	E3	E3	12	B1	B1	B1								
13	D2	F2	F2												
14	F2	D4	D2												
15	F3	F4	F3												
16	D4	D3	D3												
17	D3	D2	D4												
18	F4	F3	F4												

Table XI. The order of the significant component

Plate 1. Scratched hoses

Second, the operator or repair person may put extreme tension on the pull rope when making an adjustment. This excessive tension leads to two undesirable occurrences: first, a reduction in the lifetime of the pull rope; second, a high load on the pulley wheel leading to a reduction of the lifetime of the roller bearing inside it (see Plate 5).

To solve this problem, an electrical motor with control circuit should be designed to make automatic adjustments for the pull rope, keeping it at a constant desired tension, as shown in Figure 11. Stronger roller bearings are another possibility.

Plate 2.
Nipples and necks

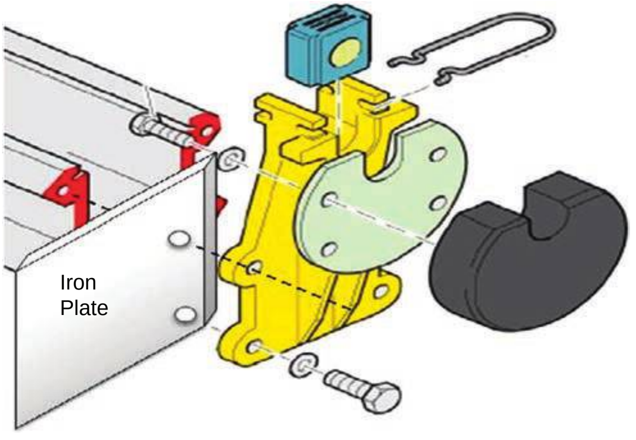


Figure 10.
Suggested plate of iron

Discussions with maintenance personal also reveal that the frequent failures in rock drill are damaging the third and fourth cup seals located inside front head (nose) of this component, as shown in Plates 6-7 and Figure 12.

A possible cause is the high water pressure inside the nose. Water is used to cool the front head and flush it during the drilling process. However, damaging the cup seals will cause water and oil to mix, leading to the adhesion of the valves used in the hydraulic system. To solve this problem, the water pressure inside the front head should be reduced by increasing the number of holes, especially in the area between the third and the forth cups seals, as shown in Plate 8. Further research is needed to confirm this explanation.

It is worth to mention that all suggestions for improvement were discussed and agreed up on together with the maintenance experts and product development team of the manufacturing company. The product development team also decided to take the suggestions on and implement them in the future.

Plate 3.
Broken pull rope

Plate 4.
Hung pull rope

6. Conclusions

The downtime analysis of drilling machines shows a significant difference between the three machines used in same mine (mine Y) in the downtime of components A (rock drill), C (hoses) and E (boom). There is no significant difference between these machines in the downtime of component D (accumulators). The analysis also finds differences in the downtime of components B (feeder) and F (cables). Components A and B used in mine X have less downtime than the same components used in the machines of mine Y, most probably as a result of the differences in the rock properties between the two mines. Further research is required to explain the differences in the downtime between the same models of the drilling machine. There is a significant difference in the downtime of component G (steering system) found in machines used within a single mine and across mines. In contrast, there is no significant difference in the downtime of component I (hydraulics) found in machines 1 and 2 used in different mines. In general, there are notable differences in the downtime of most investigated

Plate 5.
Roller bearing with pulley

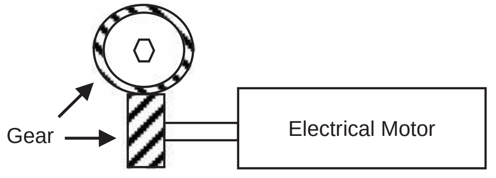


Figure 11.
Suggested electrical motor

Plate 6.
Damaged cup seal

components of all machines used in both mines. For the machines used in the same mine, three out of six components have significant differences. For machines used in both mines, five out of six components have significant differences.

The downtime analysis of drilling machines also shows that the machines' components can be ranked on their downtime, using three different scenarios (the high likelihood, the worst-case, and the best-case scenarios) based on three estimation

Plate 7.
Cup seals

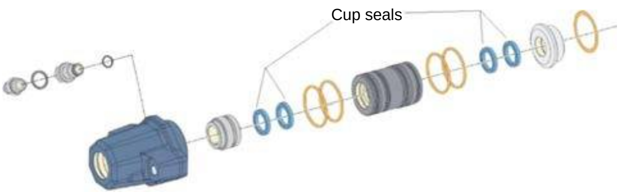


Figure 12.
Cup seals

Plate 8.
Front head (nose)
of rock drill

points of downtime. The components C2 (hoses on machine 2), B3 (feeder on machine 3) and B2 (feeder on machine 2) have more downtime ($DT_{UL} \geqslant 350$) hours per year. The downtime ($DT_{UL} \geqslant 200$) hours per year of components C (hoses), B (feeder), A (rock drill), E (boom) and G (steering system) stem from reliability problems. Because they have a high number of failures and short repair times, as shown in Figures 3-8, a DFR should be created to decrease their downtime. Overall, no maintainability problems were detected for the machines' significant components; therefore, a design for a maintainability strategy is not required. The failures of the feeder hoses are likely due to the harsh work environment during drilling. In this case, putting iron plates on both sides of the feeder may reduce the number of failures. The breakage of the feeder pull rope is due to usage and excessive tension; this can be treated and reduced by installing an electrical motor with a control circuit to keep the pull rope at a constant desired tension. Finally, increasing the number of holes between the third and the fourth cup seals inside the nose of the rock drill could solve the problem of cup seal damage.

In summary, the suggested "DFR" solution is found to be applicable. In order to judge for cost effectiveness, one should perform life cycle cost analysis to identify, if the solution is also economically viable.

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