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Full Length Research Paper

Assessment of performance of a fine coal processing plant through availability analysis and the Mann-Whitney U test for two samples

Huseyin Ankara[1] and Suheyla Yerel[2]*

[1]Mining Engineering Department, Eskisehir Osmangazi University, Eskisehir, Turkey.
[2]Civil Engineering Department, Bilecik University, Bilecik, Turkey.

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In this study, the Mann-Whitney U test for two sample and availability analysis are applied on equipments belonging to a heavy dense cyclone circuit in a fine coal processing plant. Through the results from the Mann-Whitney U test for two samples, it is determined that the coal sieves fed by the upper flow of the cyclone (S_{25}, S_{26} and S_{27}) and the coal sieves fed by the lower flow of the cyclone (S_{28} and S_{29}) are identical. Using availability analysis, the performances of the cyclone pump engine (CPE), the cyclone pump (CP) and the coal sieves are calculated. As the result of this analysis, it is found that the performances of these equipment ranges from 96.60 - 98.99% and that they operate with a high performance. As a result, it is determined that the performances of the equipment can be calculated using availability analysis and that the Mann-Whitney U test for two samples supports this analysis. Additionally, it is believed that these methods may help the monitoring of equipment in complex facilities and help improve fine coal processing plants.

Key words: Availability analysis, the Mann-Whitney U test for two samples, fine coal processing plant, cyclone circuit.

INTRODUCTION

Reliability is an important factor in the planning, design and operation of engineering systems. The increasing mechanization, the high cost of equipment, the size and complexity of modern mining systems and the increasing application of new technologies in the industry require the application of the reliability theory to achieve the desired levels of production and productivity under the prevailing economic conditions. An analysis of the production capacity of systems is necessary to increase productivity, to reduce operation costs and to improve the overall economics of mineral production capacity. Production capacity is a function of the reliability of the equipment used (Ercelebi and Yegulalp, 1993).

Equipment failures and repairs are events with stochastic properties that make the production capacity of a system a random variable. This random variable can be analyzed by the means of availability into reliability tools that are based on applied mathematics, probability theory and statistics.

Availability appears to be a more appropriate measure than reliability for measuring the effectiveness of repairable machines because it also takes into consideration maintainability, another important aspect of a system's performance (Kumar, 1989). To determine the long term performance of a system that alternates between two capability states, up and down states according to some random process, one is often primarily concerned with the long run availability of the system (Ananda, 1998).

Although availability analysis is a common tool used during the operations phase in other industries for decision and cost analysis, this analysis is not so common in the mining industry. Some studies conducted in the mining industry using availability analysis are as follows: Kumar et al. (1989), a comprehensive estimate of the operational reliability of load haul dump machines, located items or assemblies which needed an improved design to enhance the reliability and to decide the duration of the optimal preventive maintenance. Ankara (1997) carried out a study in which variations of the

*Corresponding author. E-mail: suheyla.yerel@bilecik.edu.tr, syerel@gmail.com.

Truck-Shovel System has been used to conduct availability analysis. Hosseini (1999) discussed the equipment reliability issue and addressed the need for the analysis of various performance measures through “what-if” examination of various business conditions and operation scenarios. This was achieved by developing comprehensive reliability, availability and maintenance optimization models, which were integrated with the operational characteristics of operating systems. Samanta et al. (2004), presented the reliability, availability and main-tainability of a load haul dumper machine with failure and repair data using Markov modeling.

In this study, the performances and the identicalness of equipments belonging to a heavy dense cyclone circuit are determined using the Mann-Whitney U test for two samples and availability analysis. The statistical calculations were performed using the statistical software.

METHODS

Mann-Whitney U test for two samples

The Mann-Whitney U test is employed with ordinal data in a hypothesis testing situation involving a design with two samples. The Mann-Whitney U Test is based on the following assumptions (Sheskin, 2000; Sprent and Smeeton, 2001):

- The two samples or sample pairs are independent of one another;
- The original observation values in the sample pairs are subsequently ranked;
- The underlying distributions from which the samples are derived are identical in shape.

Hypotheses for each of the sample pairs are derived from these assumptions. Null hypothesis (H_0) claims that the sample 1 (θ_1), and the sample 2 (θ_2) represent the same population. Alternative hypothesis (H_1) claims that the sample 1 (θ_1) and the sample 2 (θ_2) do not represent the same population. The following protocol is used for the Mann-Whitney U test for two samples:

- All observation values within sample pairs are arranged in order of magnitude;
- Each observation value is assigned a rank;
- If two or more observations have the same value, the average of the ranks involved is assigned to all observation values tied for a given rank;
- Once all of the observations have been assigned a rank, the sum of the ranks for each of the sample pairs is computed;
- After determining the sum of the ranks for both sample pairs, the values U_1 and U_2 are computed employing Equations 1 and 2.

$$U_1=(n_1\times n_2)+\left(\frac{n_1\times(n_1+1)}{2}\right)-\sum R_1 \tag{1}$$

$$U_2=(n_1\times n_2)+\left(\frac{n_2\times(n_2+1)}{2}\right)-\sum R_2 \tag{2}$$

Where n_1 is the number of observations in sample 1, n_2 is the number of observations in sample 2, $\sum R_1$ the sum of the ranks for sample 1 and $\sum R_2$ is the sum of the ranks for sample 2.

If n1 and n_2 >20, the lower one among the U_1 and U_2 values is taken (U) and z_h is calculated using Equations 3 - 5 (Cankuyer and Asan, 2001).

$$\mu_U=\frac{n_1\times n_2}{2} \tag{3}$$

$$\sigma_U^2=\frac{n_1\times n_2(n_1+n_2+1)}{12} \tag{4}$$

$$z_h=\frac{U-\mu_U}{\sigma_U} \tag{5}$$

The probabilities of the derived z_h emerging in the H_0 condition are determined using the z table.

Availability analysis

Consider a system which can be in one of two states, namely “up” and “down”. By “up” we mean the system is still functioning and by “down” we mean the system is not functioning; in the latter case the system is being repaired or replaced, depending on whether the component is repairable or failure (Cha and Kim, 2001). These two states could be illustrated by a drawing transition diagram (Figure 1). In this diagram, state “0” indicates that the equipment is in the operating state “up” and state “1” shows that the equipment is in the breakdown state “down” (Ankara, 1997).

Failure rate and repair rate are the two significant parameters in availability analysis. Failure rate is represented by λ and repair rate by μ. These rates are defined as the number of the failures and the repairs per unit time. λ is computed by dividing the mean time to failure (MTTF) by the unit time involved. Similarly, μ is computed by dividing the mean time to repair (MTTR) by the unit time involved. In short, λ and μ are the reciprocals of MTTF and MTTR in the unit time, respectively.

When Figure 1 is examined, it is clear that when the equipment is available at a time t, the availability of the equipment $(A(t))$ is equal to operating state probability $(P(0))$. In this case the availability is defined as in Equation 6.

$$A(t)=P(0) \tag{6}$$

If the equipment is in the failure state at a time t, on the other hand, the unavailability of the equipment is equal to the probability in the failure state $(P(1))$. Then, the unavailability is defined as in Equation 7.

$$1\text{-}A(t)=P(1) \tag{7}$$

However, the availability or the unavailability probabilities at a time $t+dt$ for the equipment to be known to be in the operating or the failure state could be determined through conditional probability. From the conditional probability definitions and equations, the state probabilities of the equipment at a time $t+dt$ and $P(1|0)$, $P(0|0)$, $P(0|1)$ and $P(1|1)$ the conditional probabilities are determined,

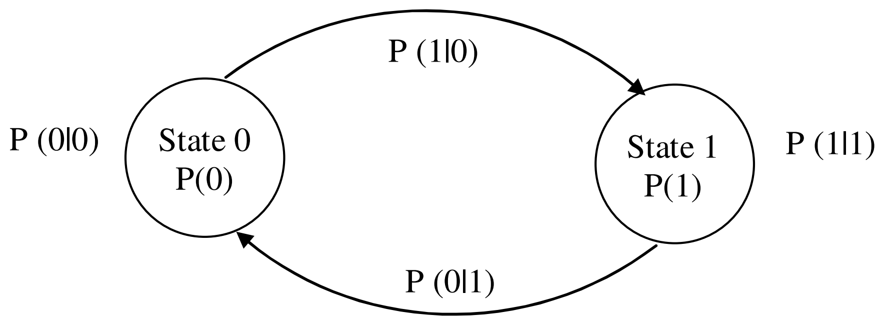

Figure 1. Transition diagram for a single unit of equipment

as shown in Figure 1. The state probabilities at a time $t+dt$ could be written as in the Equations 8 - 11.

$$P\,(1|0) = \lambda \times dt \tag{8}$$

$$P\,(0|0) = 1 - \lambda \times dt \tag{9}$$

$$P\,(0|1) = \mu \times dt \tag{10}$$

$$P\,(1|1) = 1 - \mu \times dt \tag{11}$$

Where $P\,(0|0)$ and $P(0|1)$ state probabilities are those probabilities that determine the availability of the equipment at a time $t+dt$. By using these probabilities the availability of the equipment can be computed as in Equations 12 - 13.

$$A\,(t+dt) = \left(P\,(0|1) \times P\,(1)\right) + \left(P\,(0|0) \times P\,(0)\right) \tag{12}$$

$$A(t+dt) = \left[\mu \times dt \times \left(1 - A(t)\right)\right] + \left[\left(1 - (\lambda \times dt)\right) \times A(t)\right] \tag{13}$$

When Equations 12 - 13 are arranged, Equation 14 is found as:

$$\frac{dA(t)}{dt} = \left[-(\mu + \lambda) \times A(t)\right] + \mu \tag{14}$$

It is theoretically assumed that the initial condition at a time t $\left(A(t=0)\right)$ is equal to Equation 15.

$$A(t=0) = 1 \tag{15}$$

The solution of this differential equation is written into the availability of a single equipment as in Equation 16.

$$A(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} \times e^{-(\lambda+\mu)\times t} \tag{16}$$

RESULTS AND DISCUSSION

In this study, 1 CPE, 1 CP, three cyclones, three coal sieves fed by the upper flow of the cyclone (S_{25}, S_{26} and S_{27}) and two coal sieves fed by the lower flow of the cyclones (S_{28} and S_{29}) operating in a heavy dense cyclone circuit of a fine coal processing plant are used (Figure 2). The identicalness of the coal sieves in the circuit are determined by the Mann-Whitney U test for two samples and the performances of all equipments are determined using availability analysis. However, the performances and the identicalness of the cyclones in the circuit are not determined because the time to failures for these is not recorded.

In accordance with the Mann-Whitney U test technique for two samples, the following hypotheses were established for both the time to failures and time to repairs of the sieve pairs. The hypotheses established for the time to failures of coal sieve pairs:

H_0: The coal sieves are identical in terms of time to failures.
H_1: The coal sieves are not identical in terms of time to failures.

The hypotheses established for the time to repairs of coal sieve pairs:

H_0: The coal sieves are identical in terms of time to repairs.
H_1: The coal sieves are not identical in terms of time to repairs.

The time to failures statistic (U_F) and the time to repairs statistic (U_R) for the pairs of coal sieves are determined by using the equations of the Mann-Whitney U test for two samples and are presented in Table 1. As a result of the Mann-Whitney U test for two samples, the H_1 hypothesis is rejected with a confidence of 95%, and the H_0 hypothesis is accepted, thus, it is statistically determined that the coal sieves are identical.

After determining the identicalness of the coal sieves, the availability analysis for the equipments is conducted. In order to do this, the MTTF and the MTTR values for the CPR, the CP and the coal sieves are used to calculate the

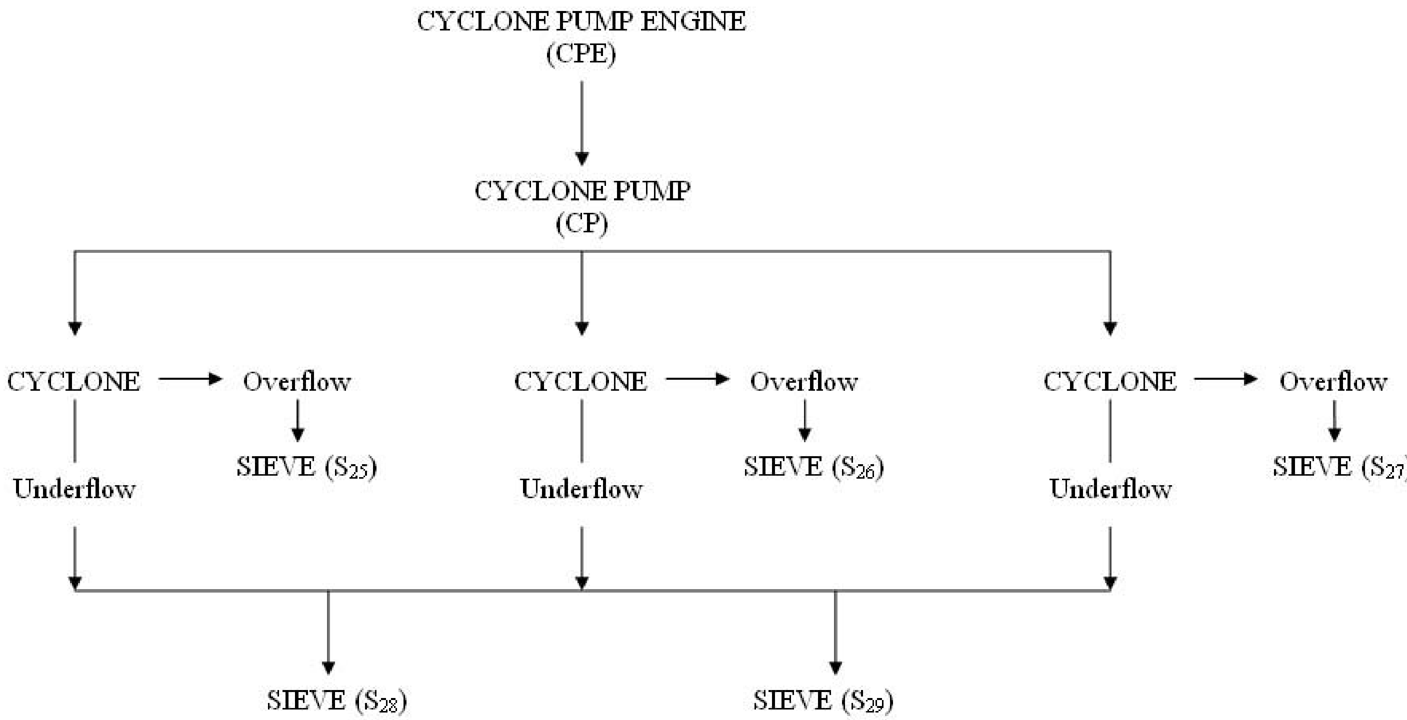

Figure 2. Heavy dense cyclone circuit.

Table 1. Results of Mann-Whiney U test for two samples.

Sieves pairs	Time to failures		Time to repairs	
	U_F-Statistic	z_h	U_R-Statistic	z_h
$S_{25} – S_{26}$	382.00	0.55	313.50	0.20
$S_{25} – S_{27}$	501.50	0.34	381.00	0.08
$S_{26} – S_{27}$	425.50	0.06	483.50	0.67
$S_{28} – S_{29}$	345.00	0.96	290.50	0.55

Table 2. The λ and μ rates of the equipments.

Equipment	MTTF	λ	MTTR	μ
CPE	13,533.00	0.000074	151.00	0.006623
CP	3,951.00	0.000253	91.00	0.010989
S_{25}	4,014.00	0.000249	41.00	0.024390
S_{26}	3,897.00	0.000257	93.00	0.010753
S_{27}	2,818.00	0.000355	99.00	0.010101
S_{28}	4,768.00	0.000210	85.00	0.011765
S_{29}	3,987.00	0.000251	46.00	0.021739

failure rates (λ) and the repair rates (μ) of each and these values are presented in Table 2. The availabilities $(t \to \infty)$ of the equipments are calculated using Equation 16, and are given in Table 3. Furthermore, a graph displaying the availabilities of the equipments in time are plotted (Figure 3). Examining Table 3 and Figure 3, it is determined that the performances of the equipments

Table 3. The availabilities of the equipments.

Availability notations	Availability equations		Availability $(t \to \infty)$
$A_{CPE}(t)$	$\frac{\mu_{CPE}}{\lambda_{CPE}+\mu_{CPE}}+\frac{\lambda_{CPE}}{\lambda_{CPE}+\mu_{CPE}}\times e^{-(\lambda_{CPE}+\mu_{CPE})\times t}$	$\frac{0.006623}{0.000074+0.006623}+\frac{0.000074}{0.000074+0.006623}\times e^{-(0.000074+0.006623)\times t}$	0.9889
$A_{CP}(t)$	$\frac{\mu_{CP}}{\lambda_{CP}+\mu_{CP}}+\frac{\lambda_{CP}}{\lambda_{CP}+\mu_{CP}}\times e^{-(\lambda_{CP}+\mu_{CP})\times t}$	$\frac{0.010989}{0.000253+0.010989}+\frac{0.000253}{0.000253+0.010989}\times e^{-(0.000253+0.010989)\times t}$	0.9775
$A_{S_{25}}(t)$	$\frac{\mu_{S_{25}}}{\lambda_{S_{25}}+\mu_{S_{25}}}+\frac{\lambda_{S_{25}}}{\lambda_{S_{25}}+\mu_{S_{25}}}\times e^{-(\lambda_{S_{25}}+\mu_{S_{25}})\times t}$	$\frac{0.024390}{0.000249+0.024390}+\frac{0.000249}{0.000249+0.024390}\times e^{-(0.000249+0.024390)\times t}$	0.9899
$A_{S_{26}}(t)$	$\frac{\mu_{S_{26}}}{\lambda_{S_{26}}+\mu_{S_{26}}}+\frac{\lambda_{S_{26}}}{\lambda_{S_{26}}+\mu_{S_{26}}}\times e^{-(\lambda_{S_{26}}+\mu_{S_{26}})\times t}$	$\frac{0.010753}{0.000257+0.010753}+\frac{0.000257}{0.000257+0.010753}\times e^{-(0.000257+0.010753)\times t}$	0.9767
$A_{S_{27}}(t)$	$\frac{\mu_{S_{27}}}{\lambda_{S_{27}}+\mu_{S_{27}}}+\frac{\lambda_{S_{27}}}{\lambda_{S_{27}}+\mu_{S_{27}}}\times e^{-(\lambda_{S_{27}}+\mu_{S_{27}})\times t}$	$\frac{0.010101}{0.000355+0.010101}+\frac{0.000355}{0.000355+0.010101}\times e^{-(0.000355+0.010101)\times t}$	0.9660
$A_{S_{28}}(t)$	$\frac{\mu_{S_{28}}}{\lambda_{S_{28}}+\mu_{S_{28}}}+\frac{\lambda_{S_{28}}}{\lambda_{S_{28}}+\mu_{S_{28}}}\times e^{-(\lambda_{S_{28}}+\mu_{S_{28}})\times t}$	$\frac{0.011765}{0.000210+0.011765}+\frac{0.000210}{0.000210+0.011765}\times e^{-(0.000210+0.011765)\times t}$	0.9825
$A_{S_{29}}(t)$	$\frac{\mu_{S_{29}}}{\lambda_{S_{29}}+\mu_{S_{29}}}+\frac{\lambda_{S_{29}}}{\lambda_{S_{29}}+\mu_{S_{29}}}\times e^{-(\lambda_{S_{29}}+\mu_{S_{29}})\times t}$	$\frac{0.021739}{0.000251+0.021739}+\frac{0.000251}{0.000251+0.021739}\times e^{-(0.000251+0.021739)\times t}$	0.9886

are high and that the circuit is utilized effectively.

Conclusion

In this study, the identicalness and the performances of the equipment from a heavy dense cyclone circuit are determined. Firstly, the identicalness of the equipment is determined using the Mann-Whitney U test for two samples. After, availability analysis is used to examine the performances of the equipment operating in a heavy dense cyclone circuit. As a result of this analysis, it is determined that performances of the equipment lie in the range of 96.60 - 98.99% and that the circuit operates efficiently. Furthermore, it is concluded that the identicalness of similar equipment, of which are found more than one in a heavy dense cyclone circuit, can be determined using the Mann-Whitney U test for two samples and this technique effectively supports availability analysis. It is determined that availability analysis and the Mann-Whitney U test for two samples can be used together in determining the performances

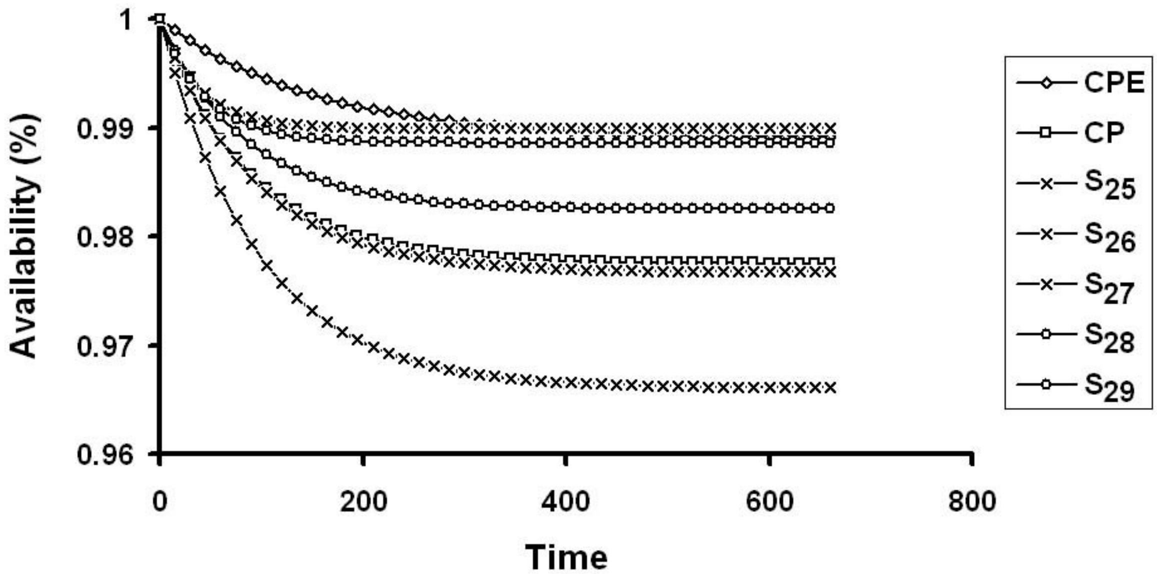

Figure 3. Time versus the availabilities

equipment operating in a plant.

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