

Article

A Critical Investigation on the Reliability, Availability, and Maintainability of EPB Machines: A Case Study

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Abstract: Tunnelling is a vital geotechnical engineering feature of underground transportation systems that is potentially hazardous if not properly investigated, studied, planned, and executed. A reliability, availability, and maintainability (RAM) analysis is one of the main practical techniques in machinery-based projects to recognize the failure and repair rates of machines during or after their operations. RAM analysis of mechanized tunneling can help to manage the project safety and cost, and improve the availability and performance of the machine. There are several methods to obtain and predict the RAM of a system, including the Markov chain simulation and other statistical methods; however, the result of the analysis can be affected by the selected method. This paper presents the results of a critical investigation on the RAM of the Earth pressure balance machines (EPBMs) used in developing an urban metro project in Isfahan, Iran. The five kilometer length of the first line of the Isfahan metro project was excavated using EPBMs over four years. After overhauling the EPBMs and making some minor changes, excavation of the second line started, and to date, about 1.2 km has been excavated by the refurbished machines. In the present study, a RAM analysis has been applied to electrical, mechanical, and cutter head subsystems of the EPBMs in Lines 1 and 2 of the Isfahan metro project over an 18- and 7-month period of machine operation, respectively. The results show that the estimated availability, $A(t)$, determined by the Markov method, is closer to reality but cannot be propagated to reliability $R(t)$ and maintainability $M(t)$ analysis. It was also revealed that by predicting the required maintenance and proper planning, the overall availability of the EPBM was improved from 45% in Line 1 to 61% in Line 2. The outcomes of this study can be used in the future planning of urban tunneling projects to estimate machine, staff, and logistic performance with the least possible error, and appropriately arrange the factors involved in the system.

Keywords: EPBM; reliability; availability; maintainability; Markov method; network modeling

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1. Introduction

A reliability, availability, and maintainability (RAM) analysis is amongst the most commonly used practical techniques in determining the performance of repairable systems [1]. Reliability is the probability of an item performing a required function under stated conditions for a specified period. Availability measures the degree to which an item is in an operable state and can be committed at the start of a mission when the mission is called for at a random point in time. Maintainability is the ability of an item to be retained in or restored to a specified condition when maintenance is performed by personnel having specified skill levels and using prescribed procedures and resources at each prescribed level of maintenance and repair.

Fault detection in the early stages of damage is essential to prevent system downtime and failure during operation; therefore, availability and reliability analysis is critical [2].

The RAM analysis helps managers to estimate machine, staff, and logistic performance with the least possible error and adequately plan the performance of the factors involved in the system. In general, reliability $R(t)$, availability $A(t)$, and maintainability $M(t)$ are obtained by three methods: renewable process (RP), non-homogeneous Poisson process (NHPP), and homogeneous Poisson process (HPP) [3]. Each of these methods has specific conditions and, consequently, probability distributions. Continuous or repairable systems could be simulated by stochastic processes, such as Markov, semi-Markov, and semi-regenerative [4]. Markov processes represent a straightforward generalization of sequences of independent random variables. These are processes without after effect. Considering this, the evolution of the process after an arbitrary time point, “ t ,” only depends on “ t ” and on the state occupied at “ t ”, not on the evolution of the process before “ t ” [3].

1.1. Application of RAM

The use of RAM dates back to the early 1960s when the probability concepts were applied to problems associated with electric power generation. Today, RAM engineering is a well-developed discipline that has branched into specialized areas such as software, mechanical, and many other engineering fields. In this regard, in oil and mine engineering, due to the machinery-based nature, RAM analysis is one of the leading systems for improving the utilization of the project [5]. Several RAM analyses for different types of mining machines have already been reported, including crushing plants [6], drum shearers in longwall coal mining, rotary drilling machines [7], and productivity of draglines [8].

With the increasing use of tunnel boring machines in recent decades, RAM analysis has also been employed in examining the performance of these machines. A brief history of this topic is available in [9]. A few researchers [10–14] have investigated TBM performance in various conditions with different methods. These studies have been completed on multiple geological and geotechnical conditions of rock or soil with experimental approaches, physical theories, or laboratory studies. However, the effects of delays and breakdowns of TBMs, two key parameters to evaluate the real performance of a machine, have not been well studied before.

1.2. Application of RAM in Mechanized Tunneling Projects

Investigating the delays of several mechanized tunneling projects, [15–17] concluded that more than 60% of the whole project delays are associated with TBM system delays. In addition, [18] suggested a general method for calculating system utilization by considering delays in mechanized tunneling projects. Citation [19] provided an alternative muck removal system for the third line of the Tabriz urban railway by studying delays during the construction of the first line. By defining a block definition diagram (BDD), [20,21] used a hybrid discrete-event simulation approach to predict the total duration of an Earth pressure balance machine (EPBM) project by considering all project delays. A few studies [22] considered RAM application in TBM projects. These researchers have all studied the effects of delays, but the impact of TBM failures and TBM’s RAM have not explicitly been investigated.

By dividing the EPBM into mechanical, hydraulic, pneumatic, water, and electrical subsystems and running a RAM analysis, [22] evaluated the EPBM’s condition using the network modeling (block diagram) and calculated the availability of the EPBM to be about 48%. The belt conveyor lines of the Tabriz urban railway line 2 were also analyzed using the same method (network modeling) by [23], and RAM values were calculated. Instead of using network modeling, for the first time [4] used the Markov chain to analyze the RAM values of EPBM for an irrigation tunnel project in India. By dividing the EPBM into four subsystems, he formed the transition diagram of the system and calculated its RAM values with related equations.

In this paper, the availability value for sections of the Isfahan metro Line 1 construction is calculated using network and Markov methods to determine the most appropriate method. Reliability and maintainability diagrams are then analyzed using the best de-

terminated method. Finally, RAM values of Isfahan metro Line 2 construction using the refurbished EPBM of Line 1 are analyzed and compared to the Line 1 values.

2. Case Study, EPBM of Isfahan Metro

The first line of the Isfahan metro starts in the northwest and finishes south of Isfahan. As seen in Figure 1, about 5 km of this line have been excavated by EPBM. The tunnels were two directional, with an excavation diameter of 6.9 m and a finished diameter of 6 m. The geology along the route comprises river sediments mainly consisting of sand, gravel, and clay, with some cemented lenses in the southern parts of the route. The general specifications of the utilized EPBM are shown in Table 1.

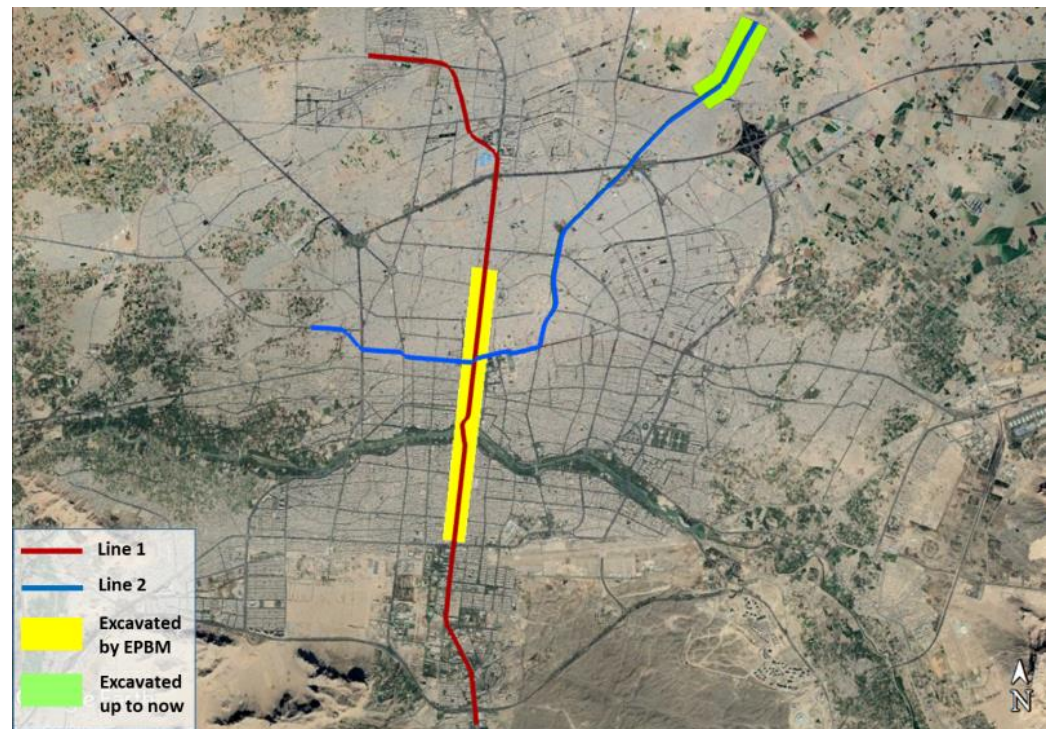


Figure 1. Isfahan metro lines (after Google Imagery @2022 CNES/ Airbus, Maxar Technologies, Map Data @2022).

Table 1. Technical features of the EPBM used in the Isfahan metro.

| Technical Features | Information |
|-----------------------------|----------------------------|
| Machine series | HK: S200 series |
| Excavation diameter | 6.9 m |
| Thrust cylinders and force | 19 pcs: 32000 kN (315 bar) |
| Cutterhead power | 3 × 315 kW |
| Maximum torque | 4700 kN.m |
| Cutterhead rotational speed | 0–4 rpm |

From the point of view of maintenance, EPBMs can generally be divided into three subsystems: electrical, mechanical, and cutterhead. The electrical subsystem includes the electronic circuits, electrical power, PLC, and communication; the mechanical subsystem consists of hydraulics, mechanical, pneumatic, and water; and the cutterhead subsystem includes the cutting tools and foam lines. These three subsystems, which include other internal subsystems, are considered for a RAM analysis of EPBMs.

3. Definitions

It is crucial to define related parameters to perform a RAM analysis. TBF and TTR parameters are defined as the time between the breakdown of the EPBM and the time

needed to carry out repairs, respectively, as shown in Figure 2. Using a database containing these parameters during a specific period for each subsystem, the mean values of these parameters can be calculated as MTBF and MTBR. From these mean values, failure rate (λ) and repair rate (μ) can be calculated as follows [3,24]:

$$MTBF = \frac{\sum_{i=1}^n TBF_i}{n} \quad \lambda = 1/MTBF \quad (1)$$

$$MTTR = \frac{\sum_{i=1}^n TTR_i}{n} \quad \mu = 1/MTTR \quad (2)$$

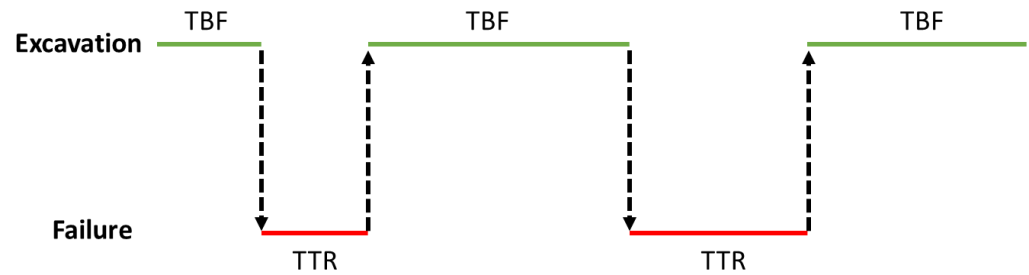


Figure 2. TBF and TTR of the machine for each subsystem.

4. RAM analysis of EPBM

After calculating TBFs and TTRs for each subsystem, a RAM analysis can be performed using the methods described in the previous sections.

4.1. Availability Analysis

As previously mentioned, network and Markov modeling are two practical methods for performing availability analysis [25]. The following will present availability analysis equations for the EPB machine used for constructing the Isfahan metro based on the three defined subsystems.

4.1.1. Network Modeling

As there is a relationship between the EPBM subsystems (electrical, mechanical, and cutterhead), availability for each subsystem, and the whole EPBM, can be defined based on network modeling using the following equations [25]:

$$A_E = \frac{MTBF_E}{MTBF_E + MTTR_E} \quad (3)$$

$$A_M = \frac{MTBF_M}{MTBF_M + MTTR_M} \quad (4)$$

$$A_C = \frac{MTBF_C}{MTBF_C + MTTR_C} \quad (5)$$

$$A_{EPBM} = A_E \times A_M \times A_C \quad (6)$$

where, A_E , A_M , A_C are the availability of electrical, mechanical, and cutterhead subsystems, respectively, and A_{EPBM} is the availability of the whole system.

4.1.2. Markov Method

When using the Markov method, the system's behavior should be independent of memory. This means that the accident behavior of the system depends only on current data and is independent of its past behaviors. The assumptions for the Markov method are [25]:

- i. All system transition rates (i.e., failure and repair rates) are constant.
- ii. All occurrences are independent of each other.

- iii. The probability of transition from one system state to another in the finite time interval dt is given by λdt , where λ is the transition rate (e.g., system failure or repair rate) from one system state to another.
- iv. The probability of more than one transition occurrence in finite time interval dt from one system state to another is very small or negligible (e.g., $(\lambda dt)(\lambda dt) \rightarrow 0$).

The first step is to develop the system transition diagram, including its subsystems, and the relation between those, as presented in Figure 3.

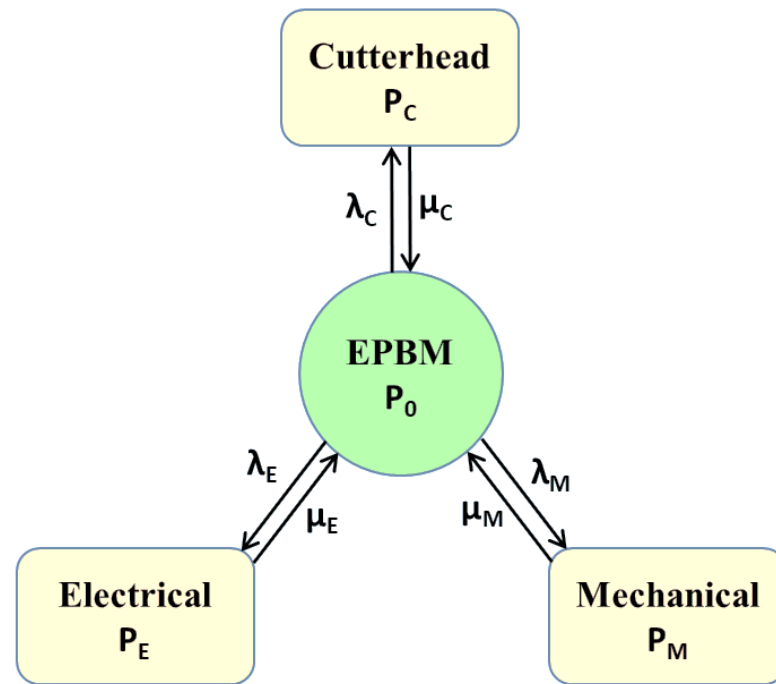


Figure 3. Transition diagram of the EPBM and its subsystem.

From the transition diagram, a system transition matrix is formed, and the probability of each subsystem is calculated.

$$M = \begin{bmatrix} X_0 & \lambda_C & \lambda_E & \lambda_M \\ \mu_C & X_C & 0 & 0 \\ \mu_E & 0 & X_E & 0 \\ \mu_M & 0 & 0 & X_M \end{bmatrix} \quad (7)$$

Since the total probability values of subsystems in a system should be equal to one, therefore:

$$X_0 = 1 - (\lambda_C + \lambda_E + \lambda_M) = 1 - \sum \lambda_i \quad (8)$$

$$X_1 = 1 - \mu_C \quad (9)$$

$$X_2 = 1 - \mu_E \quad (10)$$

$$X_3 = 1 - \mu_M \quad (11)$$

On the other hand, the probability matrix of the system can be presented as:

$$\pi = [P_0 \quad P_C \quad P_E \quad P_M] \quad (12)$$

Regarding the fourth assumption of the Markov method:

$$\pi \times M = \pi \quad (13)$$

Or:

$$\begin{bmatrix} P_0 & P_C & P_E & P_M \end{bmatrix} \begin{bmatrix} 1 - \sum \lambda_i & \lambda_C & \lambda_E & \lambda_M \\ \mu_C & 1 - \mu_C & 0 & 0 \\ \mu_E & 0 & 1 - \mu_E & 0 \\ \mu_M & 0 & 0 & 1 - \mu_M \end{bmatrix} = \begin{bmatrix} P_0 & P_C & P_E & P_M \end{bmatrix} \quad (14)$$

and also:

$$P_0 + P_C + P_E + P_M = 1 \quad (15)$$

The probability values of each subsystem can then be calculated by equalizing the two equations above:

$$P_C = P_0 \frac{\lambda_C}{\mu_C} \quad (16)$$

$$P_E = P_0 \frac{\lambda_E}{\mu_E} \quad (17)$$

$$P_M = P_0 \frac{\lambda_M}{\mu_M} \quad (18)$$

$$P_0 = \frac{1}{1 + \sum \frac{\lambda_i}{\mu_i}} \quad (19)$$

where, P_0 is the availability of the system (A_{EPBM}) and P_C , P_E and P_M are the unavailability of cutterhead, electrical, and mechanical subsystems, respectively.

The availability value of the system (A_{EPBM}) in the network modeling is not equal to one in the Markov chain. By increasing the number of subsystems, the availability value calculated by the network modeling method will always be less than the Markov method.

4.2. Reliability and Maintainability Analysis

A basic methodology for the reliability and maintainability analysis was provided by [26]. Firstly, trend and correlation tests should be conducted to choose the most suitable method for $M(t)$ and $R(t)$ analysis. These tests and analyses are performed on each subsystem, and reliability and maintainability diagrams of each subsystem are created. These methods, and how to apply them, are shown in Figure 4. Due to the series relationship between subsystems, $R(t)$ and $M(t)$ equations will be as presented below [25,27]:

$$R(t)_i = e^{-\int \lambda(t) dt} \quad (20)$$

$$M(t)_i = 1 - e^{-\int \mu(t) dt} \quad (21)$$

$$R_{EPBM} = \prod_{i=1}^n R_i = R_E \times R_M \times R_C \quad (22)$$

$$M_{EPBM} = \prod_{i=1}^n M_i = M_E \times M_M \times M_C \quad (23)$$

These equations can be changed to Markov equations with constant $\lambda(t)$ and $\mu(t)$. In other words, the probability density function of each subsystem is exponential.

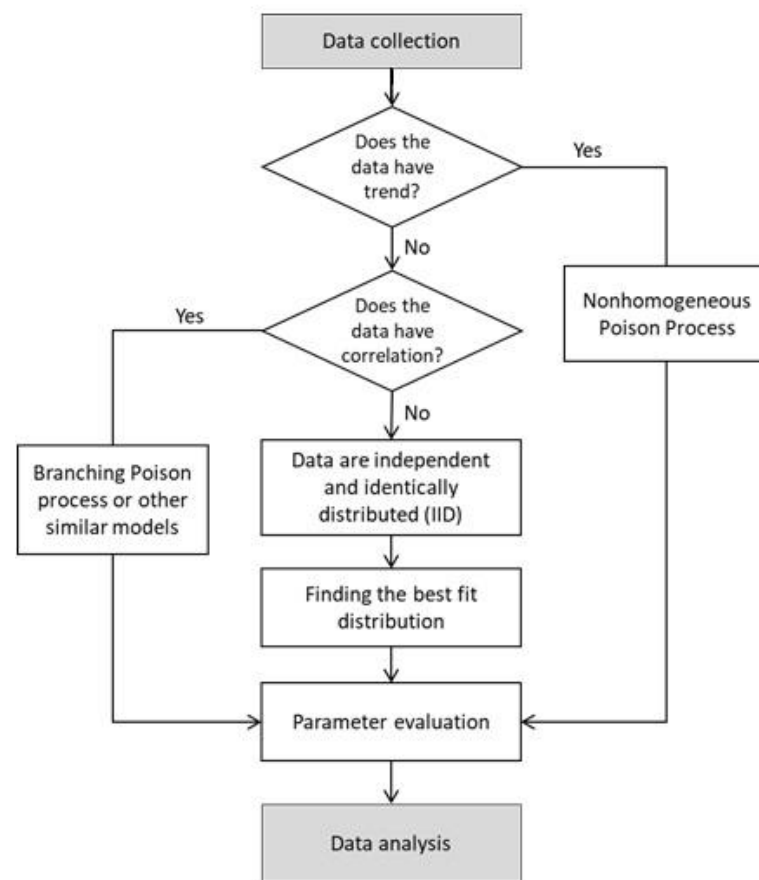


Figure 4. The process of data analysis.

5. Data Analysis of Line 1

The actual data of each subsystem had been collected for about 18 months of excavation in the Isfahan metro Line 1. Then, the collected data was used in a RAM analysis for each subsystem and the whole EPBM.

5.1. Availability Analysis of Line 1

The required values for availability analysis are given in Table 2. The availability values of each subsystem, and the whole EPBM, are then calculated using the methods mentioned above, as presented in Tables 3 and 4.

Table 2. Parameter values of the EPBM used in Line 1.

| Parameters | Unit | Electrical | Mechanical | Cutterhead |
|------------|------|------------|------------|------------|
| MTBF | h | 11.65 | 4.87 | 24.39 |
| MTTR | h | 0.69 | 1.64 | 20.02 |
| λ | 1/h | 0.086 | 0.205 | 0.041 |
| μ | 1/h | 1.450 | 0.610 | 0.050 |

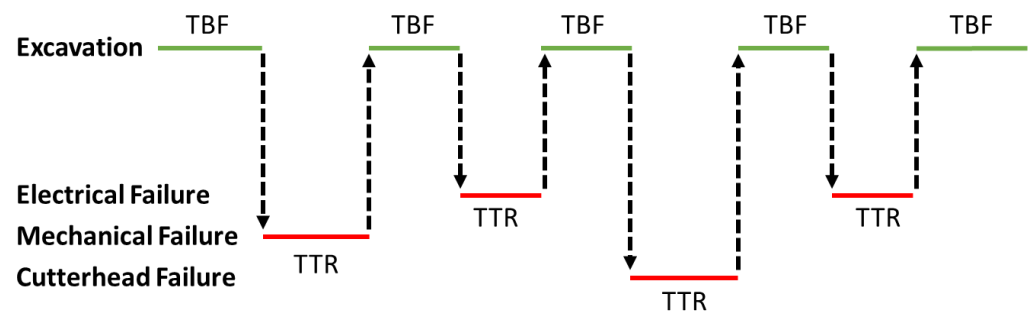
Table 3. Availability of EPBM and its subsystems in Line 1 using the networking method.

| Parameters | Values |
|------------|--|
| A_E | Availability of Electrical subsystem 0.94 |
| A_M | Availability of Mechanical subsystem 0.75 |
| A_C | Availability of Cutterhead subsystem 0.55 |
| A_{EPBM} | EPBM Availability 0.39 |

Table 4. Availability of EPBM in Line 1 using the Markov method.

| Parameters | | Values |
|------------|-------------------------------------|--------|
| P_0 | EPBM Availability | 0.45 |
| P_E | Electrical subsystem Unavailability | 0.03 |
| P_M | Mechanical subsystem Unavailability | 0.15 |
| P_C | Cutterhead subsystem Unavailability | 0.37 |

As seen in Tables 3 and 4, the EPBM availability value using the Markov model equals 45%, while it is equal to 39% using the network modeling. The real availability values should be calculated to validate the estimated availability values and find the most appropriate analysis method. This can be conducted using the complete database of Line 1 construction, based on all the TBF and TTR values for the whole system, as shown in Figure 5. Table 5 presents the mean values of TBFs and TTRs. The real availability of the EPBM can then be calculated based on these values.

**Figure 5.** The TBF and TTR of the machine for the whole system.**Table 5.** Real MTBF, MTTR, and availability values in Line 1.

| Parameters | | Values |
|------------|---------------------------------------|--------|
| MTBF | | 3.07 |
| MTTR | | 3.67 |
| A_{EPBM} | Real Availability of the whole system | 0.455 |

According to the calculations, the real availability value for EPBM in Line 1 is 45%, the same as the result of the Markov method. Thus, the Markov method is considered a more appropriate method to calculate the availability of the EPBM. It can be seen that the network modeling gives inaccurate results to this factor, primarily by increasing the subsystems of a system. The Markov method can also provide the unavailability value of each subsystem in addition to the availability value of the whole system, which is unavailable in the network modeling method. The Markov method indicates about 3%, 15%, and 37% unavailability in the electrical, mechanical, and cutterhead subsystems of the EPBM in Line 1.

5.2. Reliability and Maintainability Analysis of Line 1

First, the database's trend and serial correlation tests are carried out. As shown in Figure 6, if the data follow a trend, then the NHPP method should be used; otherwise, the serial correlation test should be performed to determine whether the data are dependent or independent. If the data are dependent, the HPP method is used; otherwise, a renewal process (RP) is used based on the probability density function with continuous distribution. Following the determination of the TBFs and TTRs for each subsystem, the two mentioned tests can be performed as presented in [28]. The Trend test is performed by analyzing the data and calculating the statistical value, U , using the following equation:

$$U = 2 \sum_{i=1}^{n-1} \ln \frac{T_n}{T_i} \quad (24)$$

where, n is the total number of failures, T_n is the time of the (n) th failure, and T_i is the time of the (i) th failure.

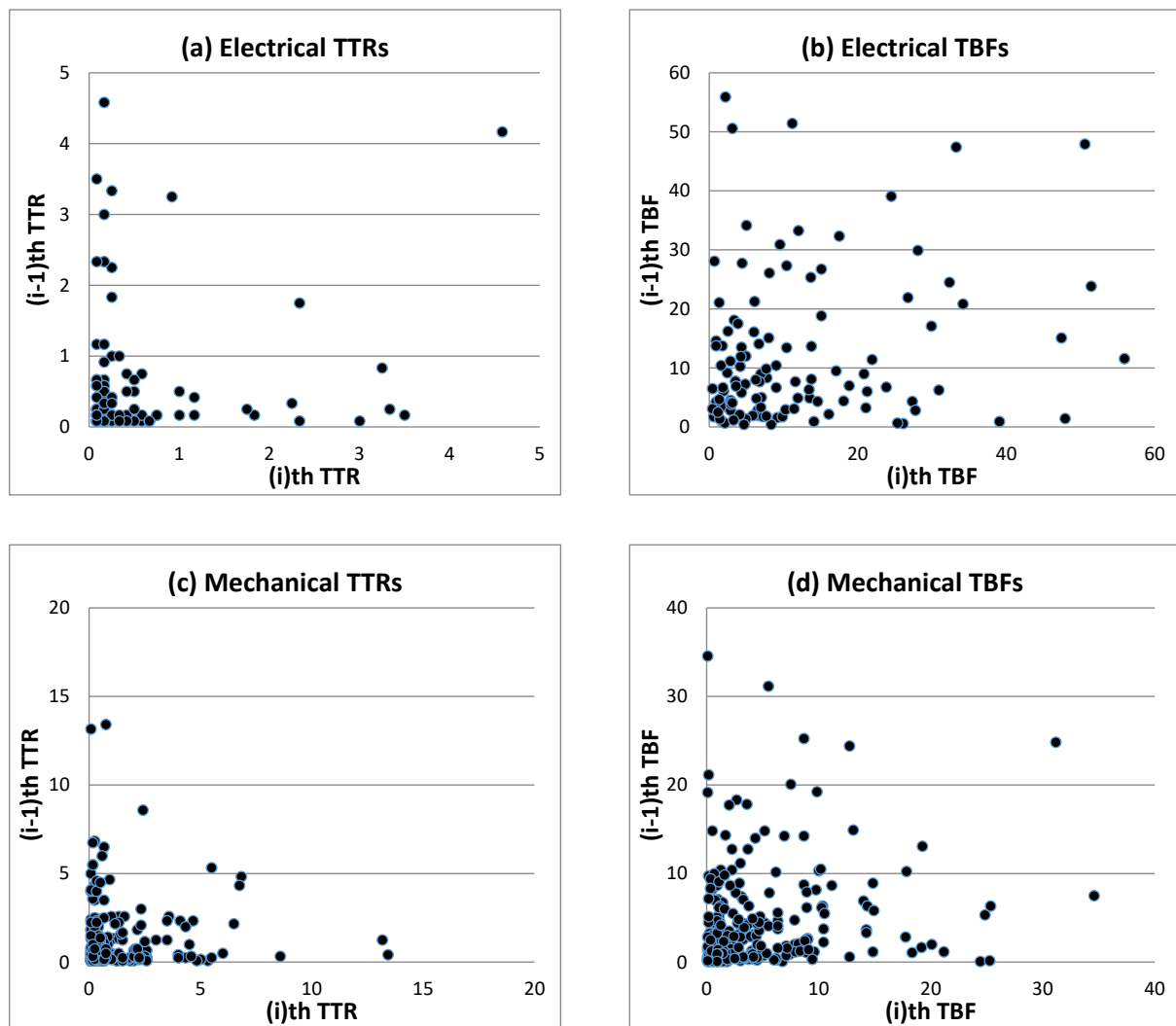


Figure 6. Serial correlation test on TBFs and TTRs of electrical and mechanical EPBM subsystems.

Under the null hypothesis of no trend, the test statistic U is chi-squared distributed with $2(n - 1)$ degrees of freedom (the number of independent grids in the system). A null hypothesis is not rejected if the test statistic U is located between the values of χ^2 in lower and upper levels of significance [29]. Serial correlation tests are performed by plotting the $(i)^{\text{th}}$ TBF or TTR against the $(i - 1)^{\text{th}}$ TBF or TTR. If the plotted points are scattered with no apparent pattern, the TBFs or TTRs are independent, and have no serial correlation [30,31].

The trend test results are shown in Table 6, which indicates that the electrical and mechanical subsystem has no trend, but the cutterhead subsystem has a trend. Figure 6 shows the results of the serial correlation test, which indicates that there is no serial correlation between TBFs and TTRs of each subsystem. Therefore, the renewal process is used for the electrical and mechanical subsystems, and the cutterhead subsystem uses the NHPP. The best fit results to determine the theoretical probability distribution for the TBF and TTR data are presented in Table 7.

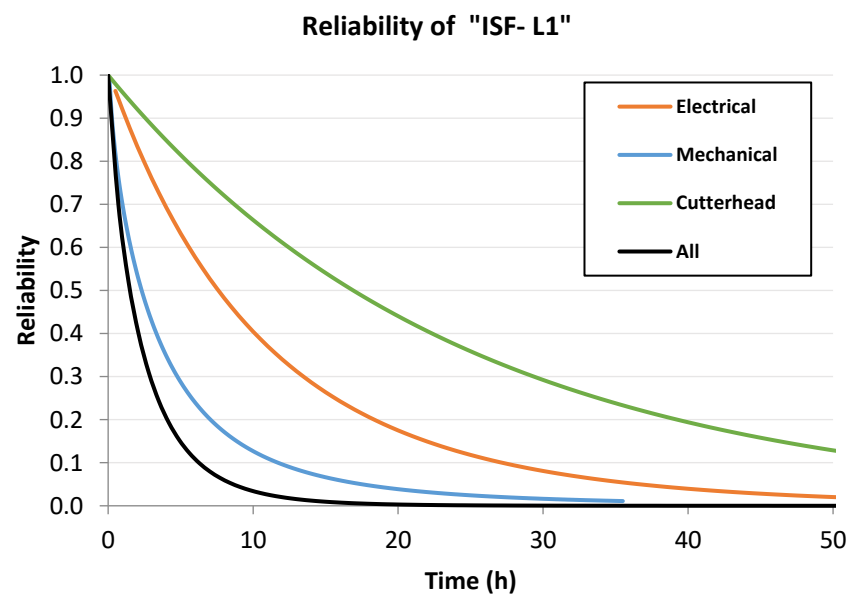
Table 6. Results of trend test on TBFs and TTRs of all subsystems.

| Subsystem | Data Set | Number of Failures | Degrees of Freedom | Calculated U | Lower Chi ² Value | Upper Chi ² Value | Rejection of Null Hypothesis | Analysis Method |
|------------|----------|--------------------|--------------------|--------------|------------------------------|------------------------------|------------------------------|-----------------|
| Electrical | TBF | 117 | 232 | 204.05 | 191.25 | 275.59 | Not Rejected | RP |
| | TTR | 117 | 232 | 261.18 | 191.25 | 275.59 | Not Rejected | RP |
| Mechanical | TBF | 280 | 558 | 521.07 | 493.97 | 624.87 | Not Rejected | RP |
| | TTR | 280 | 558 | 550.53 | 493.97 | 624.87 | Not Rejected | RP |
| Cutterhead | TBF | 56 | 110 | 8.25 | 82.42 | 140.43 | Rejected | NHPP |
| | TTR | 56 | 110 | 12.24 | 82.42 | 140.43 | Rejected | NHPP |

Table 7. Parameters of distributions for the TBFs and TTFs data of subsystems.

| Subsystem | Data set | Analysis Method | Function | K-S test | Parameters |
|------------|----------|-----------------|----------|----------|--|
| Electrical | TBF | RP | Wakeby | 0.034 | Wakeby(0; 0; 10.435; 0.10143; 0.10884) |
| | TTR | RP | Wakeby | 0.16 | Wakeby(0; 0; 0.2173; 0.66384; 0.04305) |
| Mechanical | TBF | RP | Wakeby | 0.035 | Wakeby(−2.3525; 3.7599; 3.634; 0.31306; 0.07813) |
| | TTR | RP | Burr | 0.097 | Burr(1.3098; 0.68753; 0.54189; 0.08333) |
| Cutterhead | TBF | NHPP | - | - | $\lambda = 0.041$ |
| | TTR | NHPP | - | - | $\mu = 0.050$ |

Table 7 shows that the probability distribution is not exponential in all subsystems. In other words, $\lambda(t)$ and $\mu(t)$ are not constant in all subsystems. This suggests that the Markov method cannot always be used for $R(t)$ and $M(t)$, which is contrary to the conclusions presented by [4]. The analysis of each subsystem has been determined based on the tests' results. Subsequently, reliability and maintainability diagrams for each subsystem and the EPBM have been produced, as presented in Figures 7 and 8. As seen in Figure 7, the reliability of the whole system is close to that of the mechanical subsystem, indicating that by performing scheduled repair and maintenance on the mechanical subsystem, the reliability of the entire system will also improve. Figure 8 suggests that the maintainability of the whole system significantly depends on the maintainability of the cutterhead.

**Figure 7.** Reliability of the EPBM and all subsystems in Line 1.

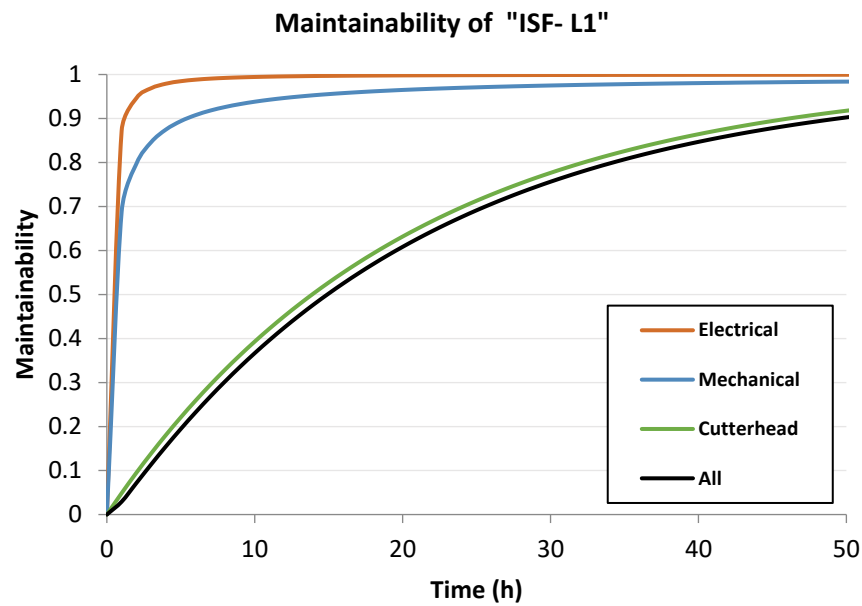


Figure 8. Maintainability of the EPBM and all subsystems in Line 1.

6. Data Analysis of Line 2

The RAM analysis for Line 1 of the Isfahan metro is presented using two different methods. The results indicate that the Markov method should be performed for the availability analysis, and the reliability and maintainability analysis should be completed according to the probability distribution function of each subsystem. The Pareto diagram was developed to see the frequency of EPBM failures in Line 1, which is presented in Figure 9. This diagram shows that more attention should be given to the mechanical subsystem concerning planning and maintenance for a successful project. Further, based on observations and the maintainability diagram, cutterhead inspection is the central aspect of maintenance time.

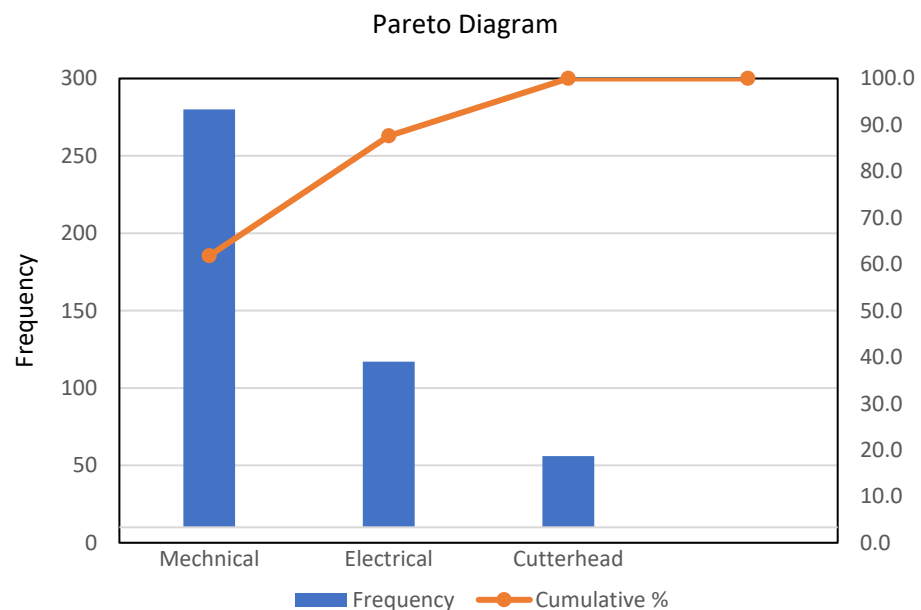


Figure 9. Pareto analysis of EPBM subsystems in Line 1.

Although the geological structure of the ground is similar in Lines 1 and 2, the geological maps of Line 2 show an increase in the cemented conglomerate sections at the face of the tunnel compared to Line 1, and the excavation must mainly be performed in

mixed face conditions (i.e., rock and soil). Thus, the decision was made to refurbish the cutterhead of the EPBM before starting excavation for Line 2 by changing the position of the foam system, replacing the grout pump, and redesigning the segment mover at the bridge area. The old and new cutter heads are presented side by side in Figure 10.

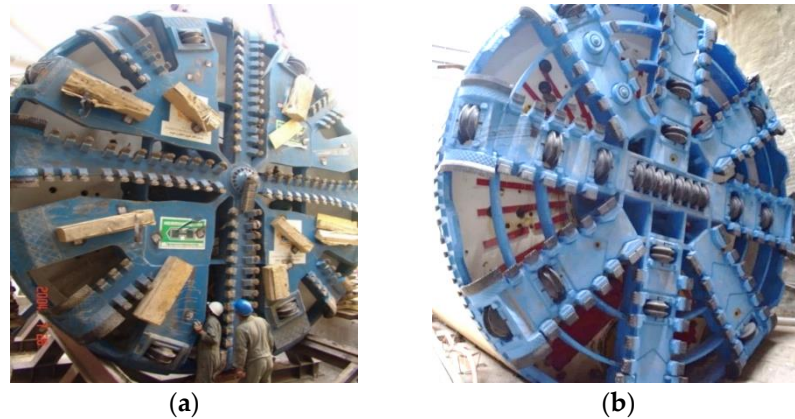


Figure 10. Cutterhead of EPBM in (a) Line 1 and (b) Line 2.

The results obtained by performing the same analysis as Line 1 for Line 2 over the initial seven months of the construction are presented in Figures 11 and 12 and Tables 8–10. An improvement is expected in the Reliability of the system in Line 2 following minor refurbishments, revised preventive maintenance operations (PM), and strict controls on mechanical and electrical parts per shift, day, week, and month. This can be further improved as the personnel gain familiarity with the machine, and more expert supervising engineers are hired. However, due to different ground conditions, it is impossible to forecast the cutterhead TTRs and TBFs in Line 2. The results show that the maintainability of the machine for Line 2 has not changed significantly compared to Line 1, although the MTTR of the mechanical subsystem improved from 1.64 to 0.87 h.

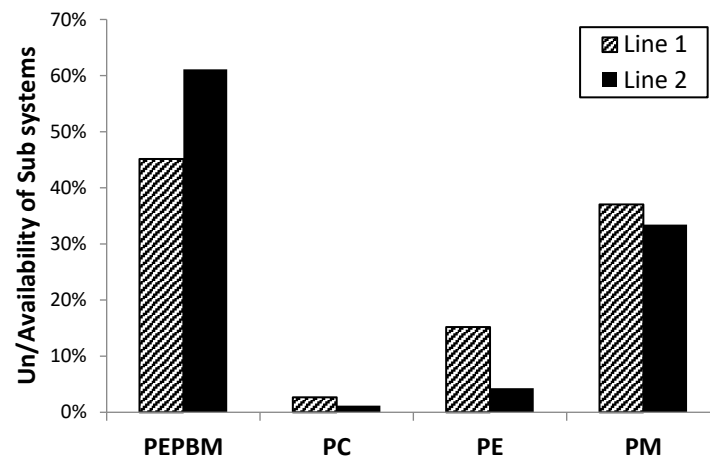


Figure 11. Availability/Unavailability of EPBM/subsystems in Lines 1 and 2.

Table 8. Comparison of MTBF and MTTR of subsystems in Lines 1 and 2.

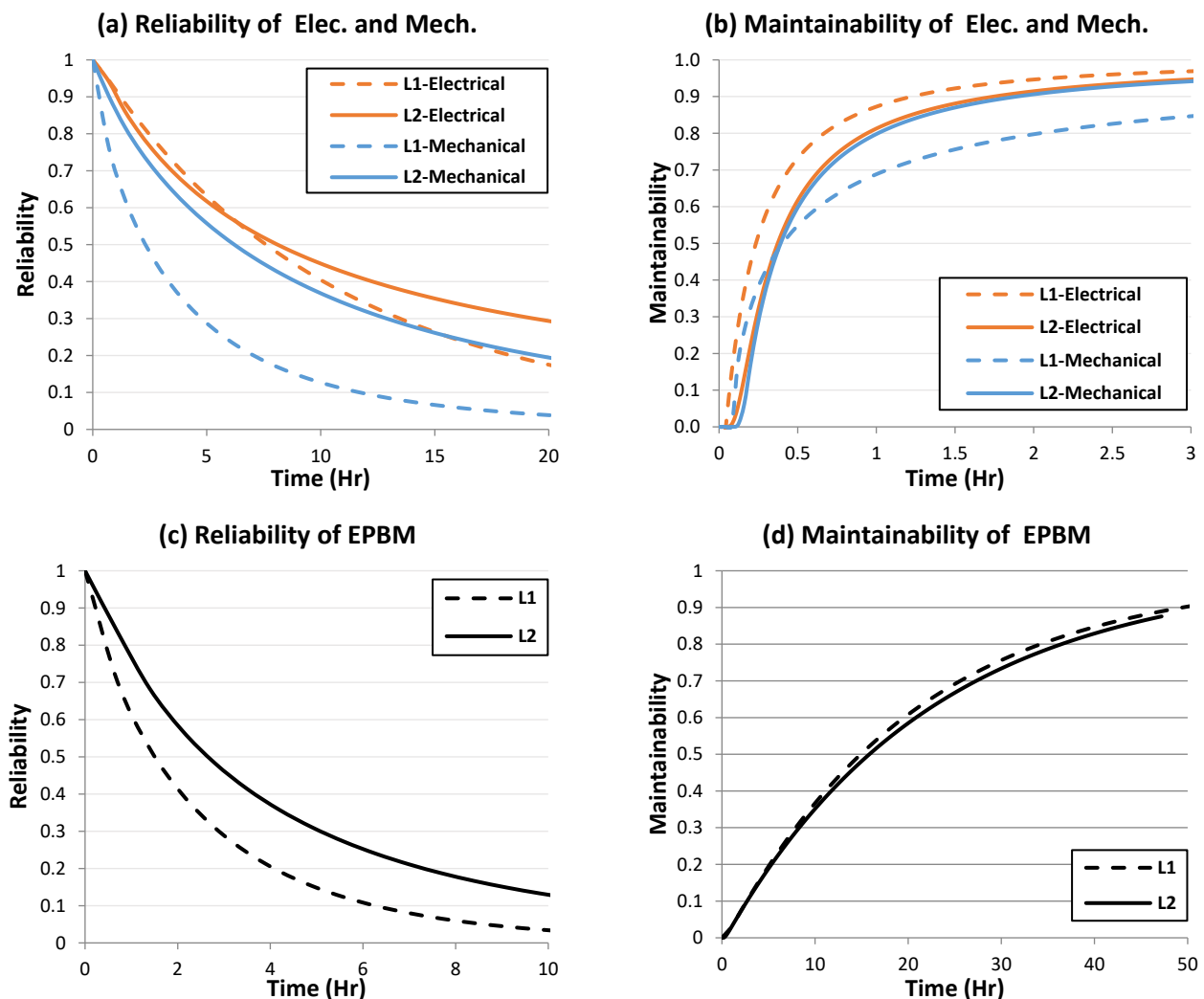
| Metro Line | Data Set | Electrical | Mechanical | Cutterhead |
|------------|----------|------------|------------|------------|
| Line 1 | MTBF | 11.72 | 4.87 | 24.39 |
| | MTTR | 0.69 | 1.64 | 20.02 |
| Line 2 | MTBF | 37.70 | 12.48 | 40.83 |
| | MTTR | 0.73 | 0.87 | 22.34 |

Table 9. Comparison of λ and μ of subsystems in Lines 1 and 2.

| Metro Line | Data Set | Electrical | Mechanical | Cutterhead |
|------------|-----------|------------|------------|------------|
| Line 1 | λ | 0.085 | 0.205 | 0.041 |
| | μ | 1.450 | 0.610 | 0.050 |
| Line 2 | λ | 0.027 | 0.080 | 0.024 |
| | μ | 1.379 | 1.144 | 0.045 |

Table 10. Availability of EPBM in Lines 1 and 2.

| Availability of System | | Line 1 | Line 2 |
|------------------------|-------------------------------------|--------|--------|
| P_0 | EPBM Availability | 0.45 | 0.61 |
| P_1 | Electrical subsystem Unavailability | 0.03 | 0.01 |
| P_2 | Mechanical subsystem Unavailability | 0.15 | 0.04 |
| P_3 | Cutterhead subsystem Unavailability | 0.37 | 0.33 |

**Figure 12.** Reliability (a,c) and Maintainability (b,d) of EPBM and two subsystems in Lines 1 and 2.

Tables 8 and 9 show that the MTTR and μ of the electrical and cutterhead are the same in Lines 1 and 2. This indicates that the required time for repairing and changing electrical parts and cutting tools cannot be reduced. In Line 2, changing the cutterhead improved the $M(t)$, but experiencing more challenging geological conditions declined the $M(t)$. Because of this, changes in the $M(t)$ values are negligible between the two lines, as seen in Figure 12.

According to Table 9, it can also be seen that the mechanical subsystem has the most improvement both in λ and μ . The reliability value has improved because of PM works. Tables 8 and 9 indicate that MTBF/ λ of all subsystems has significantly increased/decreased. This can also be due to the timely repair and maintenance during dead working times. Figure 12 shows that the reliability of the whole system in Line 2 (unlike the maintainability) has improved compared to Line 1. Reliability-based preventive maintenance time intervals for 80/65/50 percent of the reliability level for Lines 1 and 2 are 0.4/0.9/1.5 and 0.8/1.6/2.7 h, respectively.

As Table 10 and Figure 11 show, the unavailability of all subsystems has decreased for Line 2. The availability value increased from 45% in Line 1 to 61% in Line 2 by successful PM. The presence of skilled staff, effective supervisors, and improvement in some parts of the EPBM have been the key contributors to this improvement.

7. Conclusions

This paper presented a complete database of TBFs and TTRs for three subsystems (electrical, mechanical, and cutterhead) of the EPBMs in Lines 1 and 2 of the Isfahan metro project. Two methods have been used to find the availability $A(t)$ of the EPBM. The results show that the Markov process is more appropriate for deriving the availability of the EPBMs, especially when comparing systems with different subsystems. Further analysis of reliability $R(t)$ and maintainability $M(t)$ show that the Markov process cannot satisfy the processes where the probability density functions of the time between failures of the EPBM (TBFs) and the required time to carry out repairs (TTRs) are not exponentially distributed.

For the RAM analysis of the EPBMs in Lines 1 and 2, the following key findings were identified:

- i. $R(t)$, $A(t)$, and $M(t)$ of the system are dependent on its subsystems. For the EPBMs of the Isfahan metro, the mechanical and cutterhead subsystems have the most significant effect on the system's $R(t)$ and $M(t)$, respectively.
- ii. The PM has a more substantial effect on the mechanical subsystem. For the reliability level of 80%, the PM plan has improved the excavation time from 0.4 h for Line 1 to 0.8 h for Line 2.
- iii. Since the $M(t)$ of the system is close to the $M(t)$ of the cutterhead, obtaining the same cutterhead $M(t)$ for Lines 1 and 2 resulted in the same $M(t)$ for the whole system for both lines. This means that refurbishing the cutterhead has been effective despite no change in the $M(t)$ values between the lines. If there had been no refurbishment in the cutterhead for Line 2, its $M(t)$ would have probably been worsened than Line 1 due to the existence of mixed face (i.e., rock and soil) in Line 2.
- iv. The PM also had a significant effect on the availability of the system. The availability of 45% during the construction of Line 1 has increased to 61% for Line 2 after applying PM.
- v. It is recommended that for future works, an investigation be conducted on the application of other methods, such as the proportional hazard model (PHM), stratified Cox regression model (SCRM), and mixture proportional hazard model (MPHM) in EPBM projects. One of the main features of these methods is their ability to evaluate the impact of various environmental risk factors on the system's performance, which would provide an even more comprehensive analysis.

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