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RAM analysis of earth pressure balance tunnel boring machines: A case study

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Abstract
Earth pressure balance tunnel boring machines (EPB-TBMs) are favorably applied in urban tunneling projects. Despite their numerous advantages, considerable delays and high maintenance cost are the main disadvantages these machines suffer from. Reliability, availability, and maintainability (RAM) analysis is a practical technique that uses failure and repair dataset obtained over a reasonable time for dealing with proper machine operation, maintenance scheduling, cost control, and improving the availability and performance of such machines. In the present study, a database of failures and repairs of an EBP-TBM was collected in line 1 of Tabriz subway project over a 26-month interval of machine operation. In order to model the reliability of the TBM, this machine was divided into five distinct subsystems including mechanical, electrical, hydraulic, pneumatic, and water systems in a series configuration. According to trend and serial correlation tests, the renewal processes were applied, for analysis of all subsystems. After calculating the reliability and maintainability functions for all subsystems, it was revealed that the mechanical subsystem with the highest failure frequency has the lowest reliability and maintainability. Similarly, estimating the availability of all subsystems indicated that the mechanical subsystem has a relatively low availability level of 52.6%, while other subsystems have acceptable availability level of 97%. Finally, the overall availability of studied machine was calculated as 48.3%.

Keywords: *availability, maintainability, reliability, tunnel boring machine.*

1. Introduction

Earth pressure balance tunnel boring machines (EPB-TBMs) are among the most commonly applied systems in excavating and driving urban subway systems. Although having many advantages such as safer and less hazardous working environment, high automation level, and little disturbance to the surrounding ground, these machines have relatively more delays and high maintenance cost [1]. Many researchers have studied the performance characteristics of tunnel boring machines considering geological conditions and rock mass characteristics as well as some machine specifications such as thrust and power [2-5].

Successful application of TBMs requires investigations of the both ground conditions and the machine and backup system features. Availability of the TBM affects the total duration of the project, predicts the advance rate, and eventually determines the performance of a TBM. In a mechanized tunneling project, it is necessary to predict TBM performance for estimation of the project duration and costs. Advance rate, as a key parameter in mechanized tunneling, is defined as the excavated distance divided by the total operating time plus downtimes for TBM maintenance and machine breakdowns. Studies have shown that the main stops of TBMs are associated with machine's related downtimes. Jain et al. [6] have reported that more than 30% of boring time cycle is consumed due to TBM breakdowns and maintenance tasks. Laughton [7] investigations on the downtimes and delays of 10 mechanized tunneling machines showed that more than 60% of total delays are associated with TBM system delays. Frough et al. [8] studied the influence of rock mass related downtimes on the performance of TBM using a database of 682 days of machine operation and reported that the geological and rock mass related downtimes occupied about 20% of the operating times, whereas the machine related downtimes were more than 55%. Lack of detailed study and analysis on downtimes, breakdowns, and maintenance of tunnel boring machines are the main shortcomings of reported studies. A comprehensive study in this field that can noticeably improve the performance of these machines seems therefore necessary.

Reliability, availability and maintainability (RAM) analysis is a practical technique dealing with time-based failures, causes of failures, and performed maintenance activities of a given product, system, or machine. Studying the RAM characteristics of mining machines, equipment, and systems has received a great attention of researchers. In this regard, Kumar and Granholm [9] introduced the basis and methodology of reliability and maintainability analysis of mining equipment. Reliability and performance analysis of LHD machines [10-12], reliability analysis of underground haulage equipment [13], reliability analysis of crushing plant at the Jajarm bauxite mine of Iran [14], availability analysis of the main conveyor in the Svea coal mine in Norway [15], maintenance management in mechanized coal mines [16], maintainability analysis of mechanical systems of electric cable shovels [17], reliability and maintainability analysis of drum shearer machine at mechanized longwall mines [18-22], reliability and maintainability analysis of pneumatic system of rotary drilling machines [23], and maintenance plan for a fleet of rotary drill rigs [24] are the main reported applications of RAM analysis of mining equipment.

In this study, the RAM characteristics of tunnel boring machines are investigated. In this respect, an EBP– TBM manufactured by NFM Technology, working in line 1 of Tabriz subway in Iran is considered. This type of TBM is favorably utilized in Iran subways. The field data including time between failures (TBFs) and time to repairs (TTRs) were calculated for a period of time of nearly 26 month of machine operation. The results provide a practical foundation and support for the reliability, availability, and maintainability analysis of tunnel boring machines in mechanized tunneling.

2. Reliability, Availability and Maintainability (RAM) Analysis

Reliability, availability and maintainability are characteristics of a system's long-term operation and significant approaches for reducing maintenance costs and improving operation and performance.

2.1. Reliability

The reliability of a machine or system is defined as the probability that no operational interruptions will occur under specified conditions during a specified time interval. The reliability can be obtained by Equation (1).

$$R(t) = 1 - \int_{0}^{t} f(t)dt \qquad (1)$$

where $R(t)$ is the reliability at time t and $f(t)$ represents the failure probability density function [25].

2.2. Maintainability

The maintainability of a machine or system is defined as the probability that the machine or system be retained in or restored to a specified state when the repair action is performed in accordance with prescribed procedures (Eq. 2).

$$M(t) = \int_0^t f_r(t)dt \tag{2}$$

where $M(t)$ is the maintainability function at time t and f_r is the repair time probability density function [26].

2.3. Availability

The availability of a machine or system is defined as the probability that the machine or system can perform its required function at a given point in time or over a stated period of time when operated and maintained in a prescribed manner [27]. A system can be in one of two states, namely 'up (on)' and 'down (off)'. By 'up' it is meant that the system is still functioning and by 'down' it is meant that the system is not functioning (in fact the system is waiting for being repaired or replaced, depending on whether it is repairable or not). Therefore, the state of the system has a binary position:

$$X(t) = \begin{cases} 1, & \text{if the system is working at time t} \\ 0, & \text{otherwise} \end{cases}$$

where function $X(t)$ denotes the status of a repairable system at time t. The instant availability at time t (or point availability) is defined by:

$$A(t) = P(X(t) = 1) \tag{3}$$

This is the probability that the system is working at time t. Because finding an explicit expression for $A(t)$ is difficult, other measures of availability such as steady-state availability of a system have been recommended, which is defined by following equation:

$$A = Limit_{t \to \infty} A(t) = \frac{MTBF}{MTBF + MTTR} = \frac{\text{Up time}}{\text{Up time} + \text{Down time}} \tag{4}$$

where $MTBF$ is the mean time between failures and $MTTR$ is the mean time to repair [25, 28].

Therefore, TBFs and TTRs, two time-based parameters are the basic parameters in RAM analysis. The failure and repair probability density functions ($f(t)$ and $f_r(t)$) are calculated by determining TBFs and TTRs, respectively.

3. Case study, RAM analysis of EPB-TBM of Tabriz subway

Tabriz, a big city in the northwest of Iran, is located between $46°10'$ & $46°25'$ East longitude, and $38°03'$ & $38°10'$ North latitude. For solving the traffic problems, a network including four metro lines with overall length of 60 km and 160 stations is considered for this city. The length of each twin tunnel of line 1 is 8070 m with an excavation diameter of 6.88 m which after installation of the segments reaches 6 m [29]. Earth pressure balance (EPB) method is considered as the best method for construction of such tunnels thus, two EPB tunnel boring machines designed by NFM technology started the excavation of this twin tunnels in 2009. The main features of these machines are maximum torque of 8960 kN-m at 1.05 rpm, power of the cutting head of 945 kW, maximum thrust of 46,000 kN, total length of 101 m and total weight of 620 tons.

A schematic representation of these NFM machines is shown in Figure 1. These machines could be divided into front section, intermediate section and backup section. The front part (named as TBM in Fig. 1) mainly consists of cutter head, working chamber, shield, thrust cylinders, screw conveyor and erector. Connecting beams 1 & 2 include a skid for foam production, bentonite pressure vessel, dewatering pump, belt conveyor, electric supply cabinet, ventilation duct, control cabin, segment conveyor, etc. and create the intermediate part. Finally, the backup part of these machines contains 9 gantries (G1 to G9) which are schematically shown in Figure 1. These gantries accommodate electrical pumps, electrical motors, tanks, oil filtration systems, grouting pumps, air and water distributers, dewatering tank, belt conveyor, industrial air compressor, water pumps units, loudspeaker, emergency generator, air ventilator, cooling and hot water tanks, etc. Gantries are rolling on rails fixed on transverse beam placed on the lining and are intended to support components and equipment, give way to the service train up to the connecting beam and allow the personnel to move [30].

In present study, for having a proper evaluation of the reliability and performance analysis of EPB-TBM, the machine, as a system, is divided into five distinct subsystems including mechanical, electrical, hydraulic, pneumatic and water subsystems in a series configuration (Fig. 2). By calculating the reliability and availability of each subsystem, the reliability and availability of whole system could be derived.

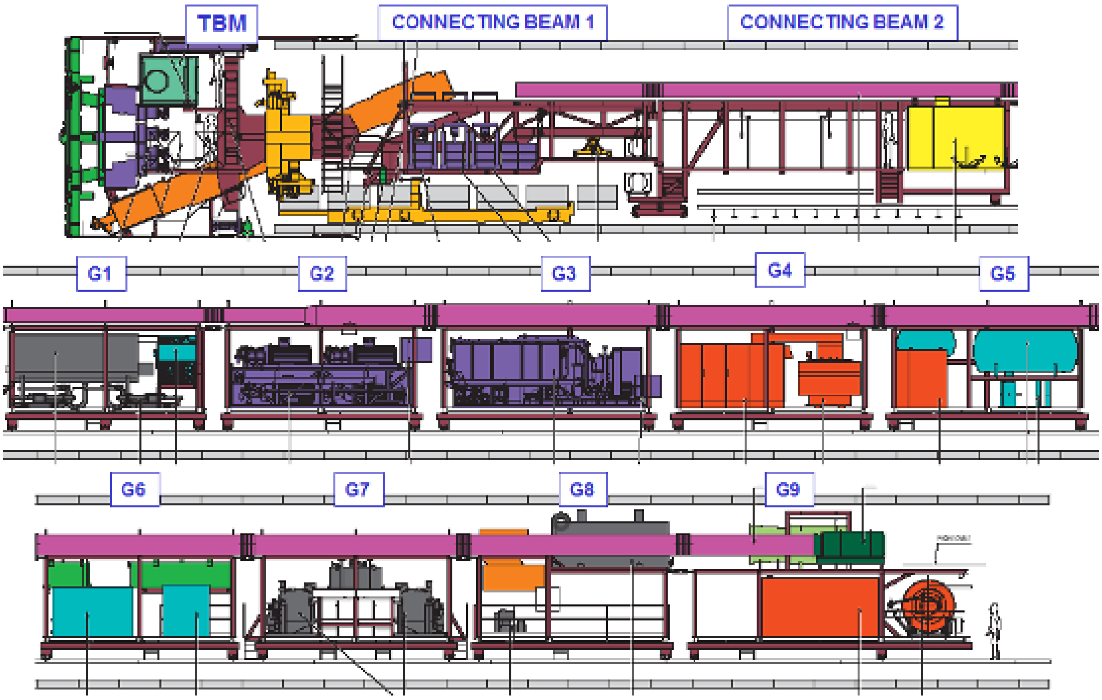

Fig. 1. Schematic representation of a NFM- EPB machine [30]

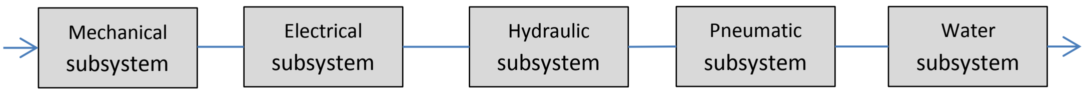

Fig. 2. Block diagram of EPB- TBM

Each of the mentioned subsystems are composed of many components and complicated circuits. The main components of these subsystems which their related failures and repairs have separately been considered as required data for RAM analysis of each subsystem are briefly listed as follows:

- The mechanical subsystem: disc cutters, scrapper bits, ripper bits, cutter head connecting ring, rotary seal, erector, screw conveyor, segment hoist, belt conveyor, tail seal, bentonite outlets, foam inlets and outlets, bentonite mixer.
- The electrical subsystem: transformers, several electric motors, electrical distribution boxes, electrically driven pumps, electric supply cabinet, high voltage (HV) cable reel, emergency generator, lighting, etc.
- The hydraulic subsystem: hydraulic cylinders, hydraulic pumps, hydraulic motors, hydraulic tank, oil filters, oil heat exchanger, hydraulic gear boxes, hydraulic accumulators, grouting hydraulic skid and hydraulic power pack cooling circuit.

- The water subsystem: industrial water distributors, water pumps unit, valves, cooling and hot water tanks, dewatering tank, dewatering pumps.
- The pneumatic subsystem: breathable and industrial air circuits and distributors, air compressors, air pumps, air tanks, air filters and safety valves.

The next step is applying two common tests including trend and serial correlation tests for determining the appropriate method for analyzing the reliability, availability and maintainability. Based on results, if a trend exists in TBFs or TTRs data, a non-stationary model such as non-homogeneous poison process (NHPP) (e.g., power law process) would be applied. Else, serial correlation test reveals the renewal process or branching poison process (BPP) for data analysis. If the available data are free from trend and serial correlation, the data are independent and identically disturbed (iid) and therefore the suitable distribution (e.g., Weibull, Gamma, Exponential, Lognormal, Normal, etc.) must be fitted [14, 31]. The Kolmogorov–Smirnov (K-S) test is generally applied for selecting the best fitted distribution [32, 33]. Finally, the functions and values of reliability, availability and maintainability for TBM can be determined.

3.1. Data collection and analysis

In RAM analysis of any equipment or system, providing an appropriate field database of failures and maintenance data is important for getting reliable and accurate results.

In this study, for the evaluation of RAM characteristics of the tunnel boring machine in line 1 of Tabriz metro, a database of times and causes of failures and maintenance activities of this machine was prepared over an operation period of 26 month. TBFs and TTRs for all of the five specified subsystems were separately calculated. The Pareto analysis showed that the mechanical subsystem has more frequency of failure and repair as compared to the other subsystems. As an example, Table 1 shows a number of 47 calculated TBFs and TTRs for the hydraulic subsystem of this machine. Also, the frequency of TBM failures given in Figure 3 has been carried out by Pareto analysis. These results indicated that the mechanical subsystem needs more inspection for maintenance than the other subsystems of tunnel boring machine.

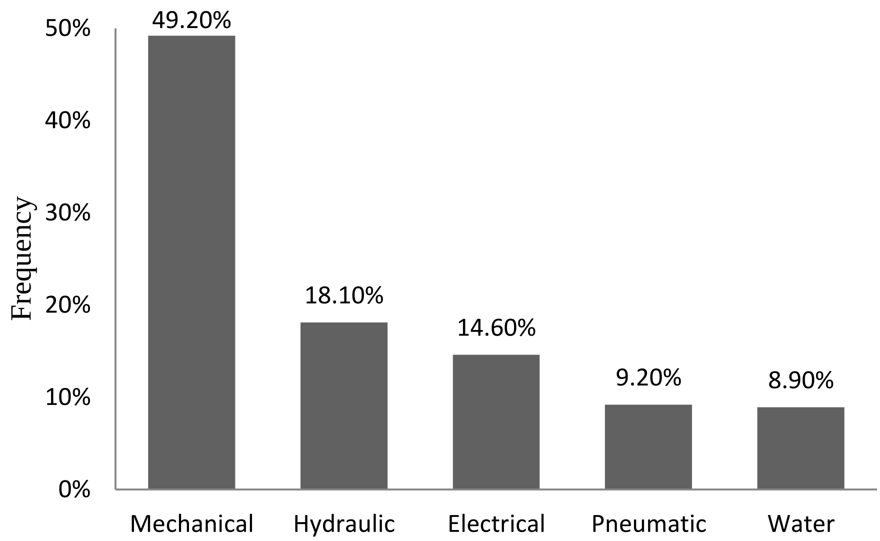

Fig. 3. Pareto analysis of studied TBM subsystems

Table 1. TBFs and TTRs of hydraulic system of studied TBM

Failure No.	TBF(h)	TTR(h)	Failure No.	TBF(h)	TTR(h)	Failure No.	TBF(h)	TTR(h)
1	0.5	0.5	17	64.83	0.33	33	190.33	0.5
2	37.5	1.5	18	101	1.33	34	13.5	0.17
3	23	0.33	19	139.83	1.17	35	143	1.83
4	0.33	1.33	20	179.83	1	36	0.67	1.17
5	47.83	2	21	3.5	6.5	37	148.67	0.33
6	9.5	2.83	22	28	0.67	38	30.17	3.67
7	31	3.5	23	76.17	0.17	39	16.83	0.33
8	154.5	2.67	24	43.33	0.33	40	1.67	2.1
9	6.5	2.33	25	23.33	0.33	41	82	2
10	65.17	0.33	26	39.17	0.17	42	100	0.67
11	83	0.67	27	25.33	0.33	43	13.33	3.67
12	198.67	0.67	28	30	0.33	44	1	2
13	38	1.17	29	4.17	0.17	45	137.83	6.33
14	15.5	2.17	30	39.33	2	46	32.83	0.5
15	0.83	2.5	31	60	1	47	15	6
16	67.5	0.33	32	0.83	0.33			

After calculating the TBFs and TTRs for all subsystems, the trend test was performed. This test is analytically performed according to Military Handbook suggestion by calculating the statistic value U from Eqution 5:

$$U = 2\sum_{i=1}^{n-1} \ln \frac{T_n}{T_i} \tag{5}$$

where the available data are failure-truncated at the n^{th} failure at time T_n. Under the null hypothesis of no trend, the calculated value of U is Chi-squared distributed with a 2(n-1) degree of freedom and this null hypothesis is not rejected if the test statistic U is located between the values of Chi^2 in lower and upper levels of significance (2.5% and 97.5% respectively) [24, 34]. The results of trend test for all subsystems showed that the TBFs and TTRs data of all five subsystems have no trend and renewal process must be applied for RAM analysis of these subsystems in present study (Table 2).

Serial correlation test is performed by plotting the i^{th} TBF or TTR against $(i-1)^{th}$ TBF or TTR. If the plotted points are scattered with no clear pattern, it shows that the TBFs or TTRs are independent and have no serial correlation [10, 18, 23]. The results of correlation test in Figure 4 indicated that there is no serial correlation in TBFs and TTRs of these subsystems. Therefore, the assumption that the data are independent and identically distributed (iid) is valid and classic statistical techniques, renewal process, is the best tool for reliability, availability and maintainability analysis of these subsystems.

Table 2. Results of trend test on TBFs and TTRs of all subsystems

Subsystem	Data set	Number of failures/repairs	Degree of freedom	Calculated statistic U	Lower Chi^2 value	Upper Chi^2 value	Rejection of null hypothesis	Analyzing method
Mechanical	TBF	128	254	294.75	212.1	299.6	Not rejected	RP
	TTR	128	254	286.78	212.1	299.6	Not rejected	RP
Electrical	TBF	38	74	87.63	52.1	99.7	Not rejected	RP
	TTR	38	74	60.19	52.1	99.7	Not rejected	RP
Hydraulic	TBF	47	92	112.4	67.4	120.4	Not rejected	RP
	TTR	47	92	100.7	67.4	120.4	Not rejected	RP
Pneumatic	TBF	24	46	41.92	29.1	66.6	Not rejected	RP
	TTR	24	46	32.89	29.1	66.6	Not rejected	RP
Water	TBF	23	44	54.04	27.6	64.2	Not rejected	RP
	TTR	23	44	49.98	27.6	64.2	Not rejected	RP

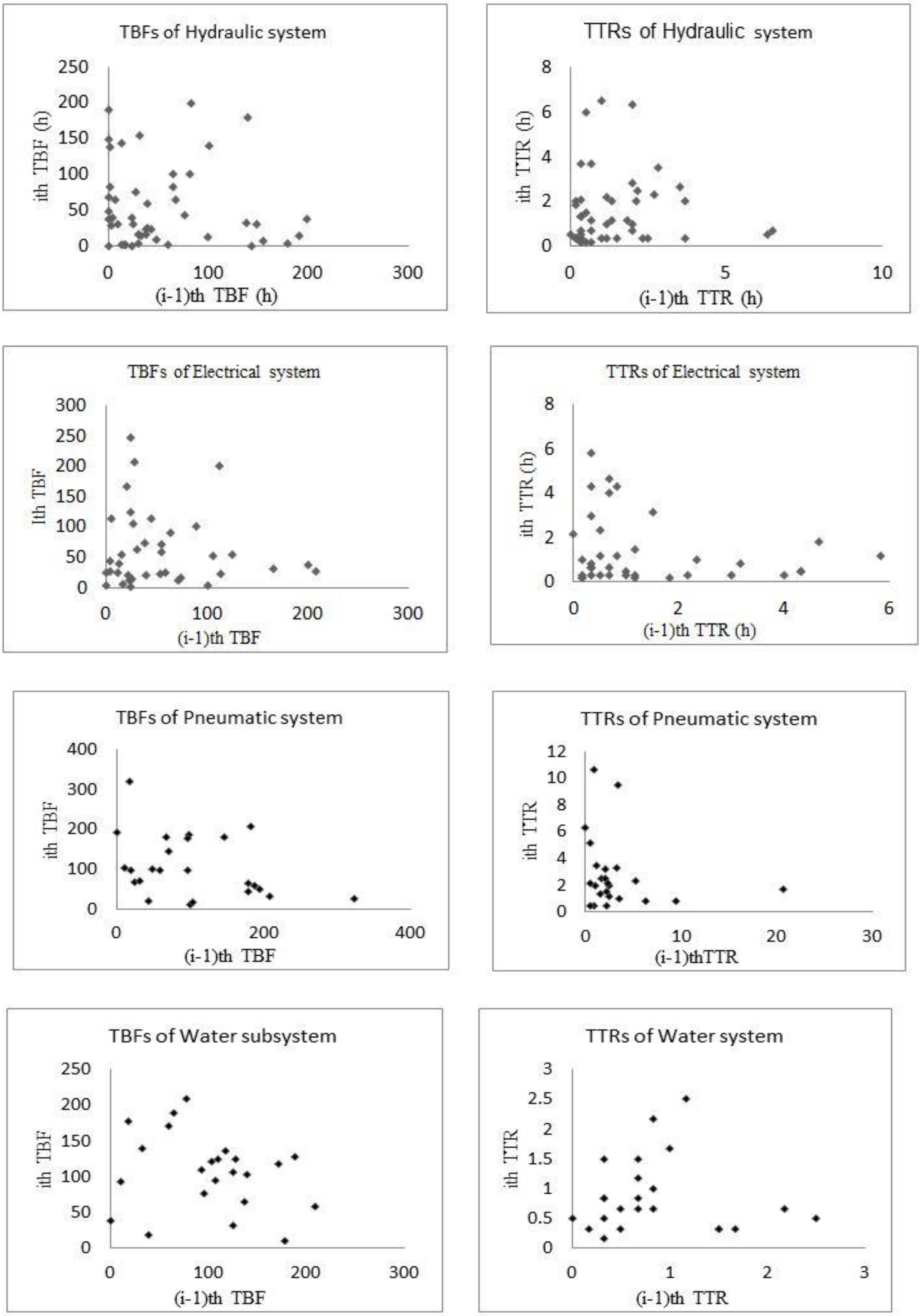

Fig. 4. Serial correlation test on TBFs and TTRs of TBM subsystems

3.2. RAM analysis

For data analysis and finding the best-fit distributions on available data, Easyfit software was applied. The Kolmogorov-Smirnov (K-S) test was used for the evaluation of goodness-of-fit and selecting the best distributions.

3.2.1. Reliability analysis

Goodness-of-fit results for determining the best-fit theoretical probability distribution for the time between failures (TBFs) data and top common distributions are given in Table 3.

Table 3. Goodness-of-fit results for determining the best-fit theoretical probability distribution for TBFs

Subsystem	Goodness-of-fit (K-S test)					Best fit	Parameters
	Lognormal (3P)	Exponential	Weibull (3P)	Gamma	Gen.Gamma		
Mechanical	0.0958	0.1279	0.0544	0.1875	0.1244	Weibull (3P)	$\alpha = 0.7183$, $\beta = 18.2498$ $\gamma = 0.5$
Electrical	0.0812	0.0859	0.0892	0.0904	0.0949	Lognormal (3P)	$\sigma = 0.93; \mu = 3.79$ $\gamma = -4.69$
Hydraulic	0.1238	0.1188	0.0908	0.1121	0.0875	Gen. Gamma	k=0.883; α=0.859 β=58.555
Pneumatic	0.1343	0.1374	0.1267	0.1362	0.1335	Weibull (3P)	$\alpha = 1.1320$, $\beta = 100.898$ $\gamma = 9.2657$
Water	0.0930	0.2837	0.0976	0.1540	0.1917	Lognormal (3P)	$\sigma = 0.0471; \mu = 7.004$ $\gamma = -994.214$

According to Table 2 there is no trend in TBFs data of subsystems and failure probability density functions of these subsystems were obtained. By applying Equation (1) and achieved parameters in Table 3, the related reliabilities of all five subsystems are plotted in Figure 5.

The reliability analysis resulted that without considering any maintenance tasks, the mechanical subsystem will be completely stopped after about 160h of TBM operation, while the water subsystem will be functional without any failures at the same time with a probability of 28%.

As mentioned earlier, the subsystems of EBP-TBM are considered as a series configuration because every breakdowns in each of these subsystems lead to the stoppage of this machine. The reliability of any machine or system in a series configuration can be achieved by Equation (6).

$$R_s = \prod_{i=1}^{n} R_i \qquad (6)$$

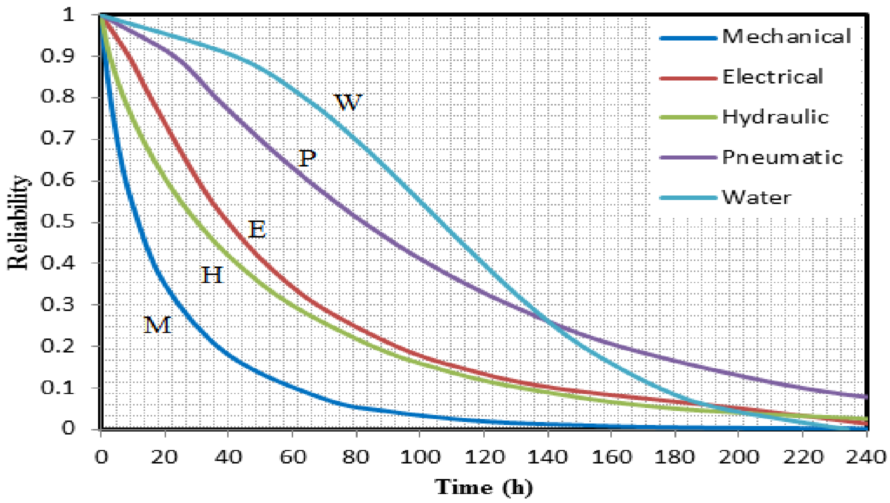

Fig. 5. Reliability of all subsystems of TBM in Tabriz metro

where R_s is the reliability of system, n is the number of subsystems and R_i is the reliability of each subsystem [35].

Therefore, the reliability of studied TBM consisting of five subsystems was attained by Equation 7 and related plot is shown in Figure 6.

$$R_{TBM} = \prod_{i=1}^{5} R_i$$
$$= R_{mechanical} . R_{Electrical} . R_{Hydraulic} . R_{Pneumatic} . R_{Water} \quad (7)$$

As can be seen in Figure 6, the reliability of TBM in line 1 of Tabriz metro sharply reduces with time and reaches zero after about 60 h of TBM operation. For increasing the reliability of TBM, it is suggested that preventive maintenance be performed at time intervals of expected level of reliability for each subsystems.

3.2.2. Maintainability analysis

Similar to the reliability analysis, the results of Goodness-of-fit for selecting the best-fitted repair probability distribution and top common ranked distributions are shown in Table 4.

Like TBFs, TTRs of all subsystems showed no trend and therefore renewal process was applied for maintainability analysis and repair probability density functions of these subsystems were obtained and therefore by applying Equation (2) and obtained parameters in Table 4, the maintainability plots of all five subsystems are illustrated in Figure 7.

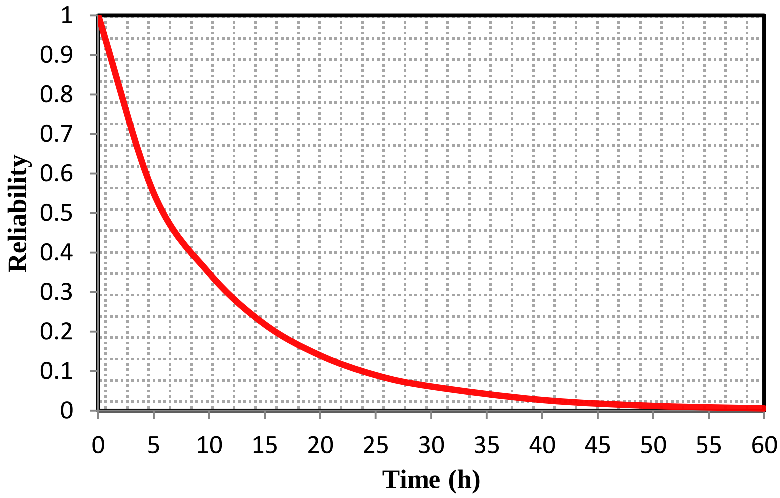

Fig. 6. Reliability of TBM in Tabriz metro

Table 4. Goodness-of-fit results for determining the best-fit probability distribution for TTRs

Subsystem	Goodness-of-fit (K-S test)					Best fit	Parameters
	Lognormal	Lognormal (3P)	Weibull(3)	Gamma	Gamma (3P)		
Mechanical	0.1528	0.1193	0.1825	0.3839	0.2347	Lognormal (3P)	$\sigma = 2.431$, $\mu = 0.621$ $\gamma = 0.167$
Electrical	0.1499	0.1401	0.1324	0.1528	0.1322	Gamma (3P)	$\alpha = 0.65, \beta = 1.58$ $\gamma = 0.17$
Hydraulic	0.1319	0.126	0.1298	0.1249	0.1375	Gamma	$\alpha = 0.926; \beta = 1.661$
Pneumatic	0.0956	0.1682	0.2159	0.1245	0.1584	Lognormal	$\sigma = 0.8185$, $\mu = 0.6680$
Water	0.1258	0.2723	0.1262	0.1351	0.1235	Gamma (3P)	$\alpha = 1.2392$, $\beta = 0.5717$ $\gamma = 0.1611$

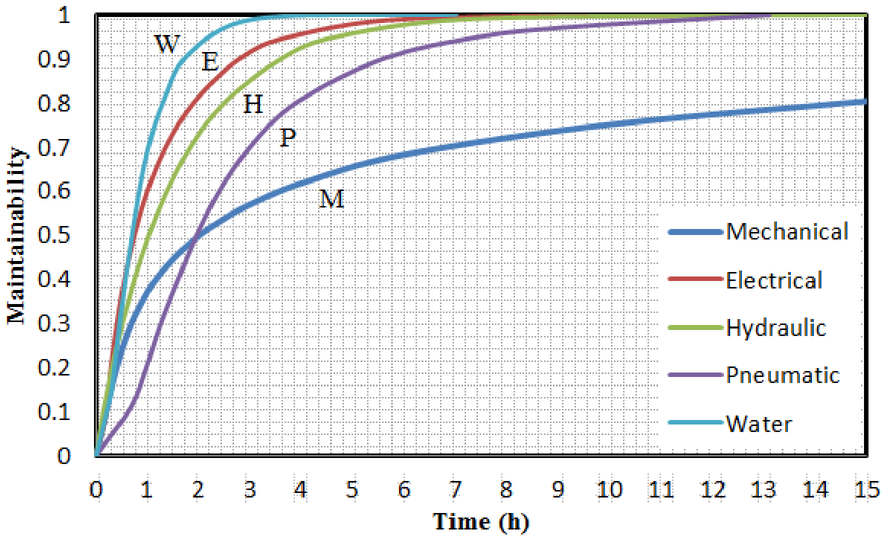

Fig. 7. Maintainability of all subsystems of TBM in Tabriz metro

From Figure 7, it is found that the water and mechanical subsystems have the greatest and the lowest maintainability respectively. It is also seen that there is nearly 90% probability that the failures of water system of EBP – TBM be repaired within about 1.6 h of repair time, while this repair times for electrical, hydraulic, pneumatic and mechanical subsystems are 42.1 h, 3.6 h, 5.6 h and 28.8 h respectively. Decreasing the repair times of mechanical subsystem can noticeably result in increasing the maintainability of this subsystem and thereby the availability of TBM in Tabriz metro project. Maintenance or repair time may be reduced by proper planning and spare parts management for increasing the availability of the machine.

Since the subsystems are considered as a series network, therefore the maintainability of tunnel boring machine was calculated by Equation 8 and the related plot is shown in Figure 8.

$$M_{TBM} = \prod_{i=1}^{5} M_i = M_{mechanical} . M_{Electrical} . M_{Hydraulic} . M_{Pneumatic} . M_{Water} \tag{8}$$

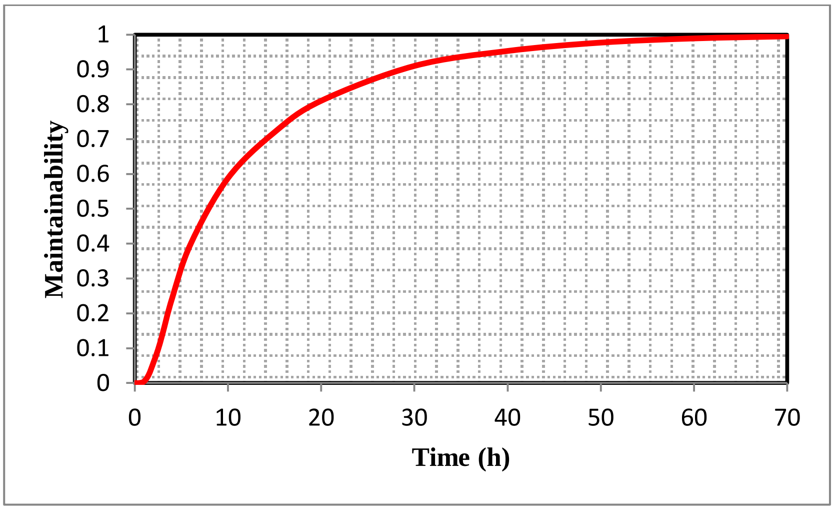

Fig. 8. Maintainability of TBM in Tabriz metro

3.2.3. Availability analysis

The availability of a system including n subsystems in a series configuration can be determined by Equation (9).

$$A_{system} = \prod_{i=1}^{n} A_i \tag{9}$$

Table 5 shows the MTBF, MTTR and availability of all subsystems of studied TBM. The mechanical subsystem with low MTBF and high MTTR has the lowest availability and is the critical subsystem for improving the reliability and availability of TBM in construction of Tabriz metro, line 1.

Table 5. Availability of all subsystems of TBM in Tabriz metro

Subsystem	MTBF	MTTR	Availability
Mechanical	22.44	20.24	0.526
Electrical	61.67	1.37	0.978
Hydraulic	54.57	1.54	0.972
Pneumatic	106.19	2.97	0.973
Water	106.45	0.87	0.992

By calculating the availability of all five subsystems, the availability of EPB-TBM in construction of Tabriz metro, line 1, was obtained as 48.3% (Eq. 10).

$$A_{TBM} = \prod_{i=1}^{5} A_i = A_{Mechanical} . A_{Electrical} . A_{Hydraulic} . A_{Pneumatic} . A_{Water} = 48.3\% \tag{10}$$

Therefore, in this study by considering the machine related downtimes a real availability and utility of TBM was calculated which has not been considered in previous studies and can result in an appropriate time planning and cost control in same mechanized tunneling projects.

4. Conclusions

In this study, a complete database of all failures and performed repairs of the NFM EBP – TBM in line 1 of Tabriz metro project over an interval of 26 months of machine operation was prepared. For having a comprehensive study on RAM analysis of TBM, this machine was divided into five distinct subsystems including mechanical, electrical, hydraulic, pneumatic and water subsystems in a series configuration. Time between failures (TBFs) and time to repairs (TTRs) of these systems were calculated separately and classified in a chronological order. According to the trend and serial correlation tests renewal process was considered as the best method for analysis and modeling the RAM of other subsystems.

Reliability and maintainability functions and related plots for all subsystems were calculated and represented. As a result, the reliability of studied TBM reaches zero after about 60 h of machine operation. Also it was revealed that the mechanical subsystem with the most failures has the lowest reliability and maintainability. If the reliability and maintainability of the TBM requires to be improved, the efforts should be firstly concentrated on improving the reliability and maintainability of the mechanical subsystem, because this subsystem has the largest effect on reliability and maintainability of the tunnel boring machine.

Furthermore, the availability of all subsystems was calculated and the results showed that the mechanical subsystem has a low availability of 52.6%, while other subsystems have acceptable availabilities of more than 97%. Finally the availability of the EPB-TBM in line 1 of Tabriz metro project was obtained as 48.3%. This value can be applied as the real utility of TBM in Tabriz metro project and also generalized to same mechanized projects with NFM machines for studying the advance rate and performance analysis of tunnel boring machines. For increasing the reliability and availability of TBM, it is suggested that preventive maintenance be performed at time intervals of expected level of reliability for each subsystem and also more skilled maintenance crew and spare parts management be applied.

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