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# Simulation of tunnel boring machine utilization: A case study

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**Abstract**
Utilization is one of the main managerial factors that is applied for construction process analysis well. It directly affects the project duration and construction costs. Therefore, a utilization study in tunneling projects is essential. In this work, the utilization of an earth pressure balance Tunnel Boring Machine (TBM) in Tabriz urban railway project was studied using the Monte Carlo simulation approach. For this purpose, the unit operation during one working shift such as boring time, ring building time, and locomotive travel time was recorded and saved in data base. In addition, the general down times such as TBM and back-up system maintenance, surface and tunnel logistic maintenance, cutting tools' replacement, and locomotive delay times were recorded and considered in simulation. The results of this work show that the mean simulated project duration time of case study TBM is approximately 859 shifts and close to the real data with a difference of 0.92%. Finally, the average estimated utilization factor was found to be approximately 14%.

**Keywords:** *Tunnel Boring Machine, Utilization, Simulation, Down Time.*

## 1. Introduction

Tunnel boring machines (TBMs) are large, heavy, and so capital intensive equipment. In mechanized tunneling, the economic and technical condition of projects is directly dependent on TBM performance and utilization. Performance and utilization are two dominant measures that enable us to study the tunneling process well, and lead the project designers to get better operational condition. So far, many studies have been done on developing practical models for performance prediction of TBMs. The main focus of performance prediction studies is the prediction of the TBMs' advance rate (AR). These studies have mainly tried to find out the relationship between the rock mass characteristics and the machine performance. For instance, Bieniawski et al. (2006) have proposed a rock mass excavability (RME) system to be applied for the direct estimation of AR [1]. A similar approach has also been introduced by Barton (1999, 2011) through the use of QTBM system, which has been applied successfully during the past decade. Shaheen et al. (2009) have develop a system to calculate the advance rate of TBM, considering various factors including the parameters of soil, machine, operator experience, and shift organization. The influence of all the mentioned parameters has been evaluated with a fuzzy logic expert system to predict the advance rate of a TBM project [2]. Donghai et al. (2010) have estimated the penetration rate of the tunnel excavation based on the rock mass classification. They studied the TBM system under different geological conditions, and the impacts of different cutter head thrusts, which have been chosen in a reasonable range according to previous experiences, have been analyzed [3]. Frough et al. (2013) have applied Rock Engineering System (RES) to calculate the geology and rock mass related downtimes index (GRDi) [4]. Copur et al. (2014) have presented a model to predict daily advance rates of EPB-TBMs in a complex geology in Istanbul [5]. Khademi et al. (2010) have developed semi-theoretical and empirical models to incorporate the impact of joints and rock mass characteristics in the estimation of advance rate [6].

In research works with focus on utilization, logistical processes, interdependencies, and downtime of the whole construction operations have been generally studied and analyzed. As outstanding research works, Duhme et al. (2013) have developed a generalized function model based on a functional analysis of different projects [7]. Sadri et al. (2013) have presented the simulation of a TBM supply chain to develop a tool for evaluating the effects of disturbance factors e.g. damaged train and segment transport to the working face on productivity of TBM [8]. Dehghani et al. (2016) have built up a wide database and applied the dimensional analysis method to develop a comprehensive mathematical equation to calculate the TBM penetration rates. Finally, the probability distribution function of the TBM penetration rate was calculated using the Monte Carlo simulation method [9].

Uncertainties in production cycles and other activities make that the mechanized tunneling is a stochastic process. Therefore, in order to better study these systems, the simulation approach could provide better results for analysis and predictions. Simulation generally offers significant opportunities to model probabilistic phenomena that are often encountered in construction. Activity durations, random resource branching, breakdown of equipment, arrival processes e.g. weather, material delivery, work orders, design drawings, availability of crews, and quality of work completed are only a few of the processes that can be probabilistically modeled [10]. In addition, when flexibility in modeling logic and knowledge is required to formulate a model and find out the integrated solution in complex systems, simulation can be an efficient and effective method [11-13].

Tunnel construction operation can be suited with the Monte Carlo simulation method because this construction process is based upon the input parameters that are likely to vary within a range of values that depend on unpredicted events. As one of the unique approaches, Roy and Mohammad (2007) have suggested a simulation model for application in an actual micro-tunneling project conducted at Louisiana Tech University. The aim of this work was to evaluate the effects of different soil conditions on the productivity of micro-tunneling operations [14].

In this research work, a simulation-based approach is presented to analyze the utilization of TBM. The aim is to find the distribution function of TBM utilization during the whole tunneling project life to predict it in future applications. The applied data is collected from an Erath Pressure Balance (EPB) TBM from Tabriz urbane railway project in Iran.

## 2. TBM operation and downtimes

Tunneling projects are constructed in various geological conditions varying from hard massive rocks to very soft sedimentary layers. Tunneling is a cycle process that consists of excavation, ground support, mucking, and lining [14, 15]. When a shield machine is used in unstable soil containing water, instability of the face must be avoided by applying a support pressure [16]. Tunneling machines with earth pressure balance support provide support to the face through removed excavated soil. The excavation chamber of the shield is closed from the tunnel by a pressure bulkhead. In stable ground, the earth pressure balance machines (EPBM) can also be operated in open mode without pressurization with a partially-filled excavation chamber [15]. Excavated materials should be transferred to the shaft with muck removal system. The main options in mechanized tunneling for muck removal are the muck car/rail method and continuous conveyor. In a muck car system, muck cars are loaded with the excavated material and these muck cars are pulled to the shaft by a locomotive on the rail system. In a continuous conveyor belt system, a conveyor belt runs the entire length of the tunnel and transfers the excavated material to the shaft.

As mentioned earlier, one of the powerful measures for evaluation of tunneling process is the utilization of TBM. Utilization is one of the key performance indicators that is mostly affected by the type of operation, management, maintenance, and geological conditions [4]. The TBM utilization factor (U) has a direct impact on the total project duration and costs, and is calculated by Equation (1).

$$U\,(\%) = \frac{\text{Boring Time}}{\text{Total time}} = \frac{T_b}{\sum T_i} \tag{1}$$

The total time $\sum T_i$ is the summation of the main activities duration and down times in tunneling process [17]. In many cases, the working days (number of days planned for working, which is generally the total calendar days minus holidays) are used for calculating AR and the Utilization

(U). The relationship between ROP (rate of penetration), AR and, U can be simply stated as:

$$AR = ROP \times U \times T \quad (2)$$

where T is the total time per shift or working day and ROP is the rate of penetration in meters per hours (m/h). This simply shows that any increase in utilization can directly influence the advance rate. It also means that even in operations where high ROP can be achieved, the tunneling rate could still fall short of expectations if the machine utilization is low [18].

In this work, to simulate the EPB mechanized tunneling system, this process is broken down to production cycles in one working shift. Depending on the type of machine, production cycle will be different in each shift. The basic operation in EPB tunneling with one train transportation system consists of the following times:

- $T_b$: TBM advance or boring time
- $T_r$: ring building time (installing support segments)
- $T_{loc}$: locomotive travel time (transfer of excavated material from the face to the shaft and transfer of segments and other materials used in the construction of tunnels to TBM)
- $TD_{loc}$: locomotive delay time

Locomotive travel time Tloc for each cycle can be calculated by Equation (3):

$$T_{loc} = X \times \left( \frac{1}{V_1} + \frac{1}{V_2} \right) + TD_{loc} \quad (3)$$

where X is distance from shaft, $V_1$ is locomotive speed when travel to TBM and $V_2$ is locomotive speed when travel to shaft. In addition to the main operations done per cycle in each working shift, other down times also exist as fallow:

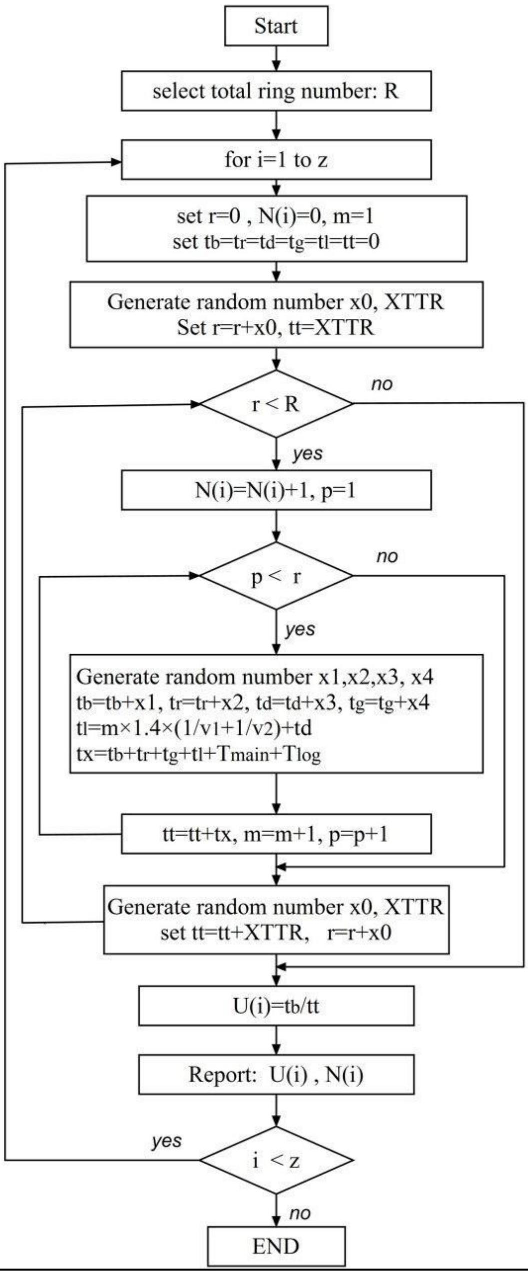
- $T_{main}$: TBM and backup system maintenance down time
- $T_{log}$: surface and tunnel logistics maintenance down time (portal crane, concrete batching Plant, tunnel dewatering system, locomotive, and train system)
- $T_{cut}$: cutting tool change down time
- $T_{gta}$: general tunneling activities time (mapping, cleaning, lunch break, shift change, rail, and service line extension)

According to the data collected from each working shift, TBM and logistics system maintenance down times are calculated for each cycle as minute/cycle or minute/ring, and are added to the time of each cycle. Cutting tool changing down time is another important activity that can affect the total project time. The cutting tool change operations of EPBs are performed by means of hyperbaric interventions. The total downtimes for the changing of the cutting tools in hyperbaric intervention includes preparation, cutting tool changing, and post-process activities. In this work, the reliability and maintainability functions are used to predict the number of stoppages and the total downtime due to the cutting tool change. The reliability and maintainability characteristics can be determined by the analysis of ring between stoppage (RBS) and time to repair (TTR) historical datasets.

In summary, all of the mentioned variables are important to calculate the utilization of the mechanized tunneling system. Therefore, the total time, which is equal to the summation of the main activity duration and down times, is calculated by Equation (4):

$$\sum Ti = T_b + T_r + T_{loc} + T_{main} + T_{log} + T_{gta} + T_{cut} \quad (4)$$

A discrete-event simulation (DES) model was used to simulate the tunneling process. For this purpose, probability density functions of the advance time, ring build time, general tunneling activity times, and locomotive delay time for the one operating cycle time are determined using the available data. During the simulation iterations, random values are generated and assigned to each input parameter according to their specified cumulative probability distribution function. The simulated utilization value for each iteration number is calculated and saved for the rest of analysis. Figure 1 presents the flowchart of the applied discrete-event simulation for estimation of the utilization and expected number of stoppages for cutting tools change.




Variables: z: number of simulation, R: total ring number, *U*(i): utilization factor, *N*(i): number of stoppage, r: number of ring between stoppage, XTTR: time to repair for cutting tools change, x1, x2, x3, t4

**Figure 1. Flowchart of applied discrete-event simulation.**

## 3. Simulation of TBM utilization: case study in Tabriz urban railway

The case study of this research work was done on EPBTBM in the Tabriz urban railway project. The applied data for simulation was collected from shift reports during the excavation of a tunnel with a length of 3360 m and a diameter of 6.88 m including 2400 rings. These rings will be formed by five normal segments and one key segment (5+1).

The working schedule was two shifts per day and 12 hours per shift. The tunnels are going through the geological structures, which are mainly composed of the gravely-sand, sandy-silt, clay-sand, and silty-sand formations.

After data collection, preliminary statistical analysis was carried out on the raw data to filter out and clarify the available data. For instance, as shown in Figures 2 and 3, the actual values for the advance time and ring building time in each operational tunneling cycle varied from 22 to 125 minutes and 11 to 100 minutes, respectively.

In order to build up the simulation process, the analysis was continued by fitting the best probability density functions on the basic utilization parameters such as the advance time, ring build time, general tunneling activity times, and locomotive delay time. The best-fitted functions and related parameters are presented in Table 1. The probability density function plot of TBM production cycle activities are shown in Figure 4. The TBM and logistics system maintenance downtime for each cycle was considered as 25 and 12 minute per cycle based on the available data. The loaded and unloaded locomotive speed, respectively, were 4 and 9 meters per minute.

In order to determine the reliability and maintainability characteristics of the cutterhead of TBM, the trend and serial correlation tests, as two common methods for the identically and independently distributed (iid) testing, were applied on sets of data [19, 20]. The results of the mentioned tests reveal that the RBS and TTR data are independent and identically distributed, and the renewal process approach could be applied for analysis. After confirming the hypothesis of the iid statistical analysis carried out by fitting the best distribution function on two sets of data. the Kolmogorov-Smirnov (KS) test was applied to determine the best-fitted distributions, and their parameters were estimated using a maximum likelihood estimator (MLE). The analysis shows that the weibull and log-logistic distributions are the best-fitted distributions for the RBS and TTR data. Table 2 presents the results of the statistical analysis in details.

After analyzing the raw data, as presented in Table 1, Table 2, and Figure 4, the simulation process was carried out based on the cumulative best-fitted density functions. The main goals of simulation were project duration time (shifts) and TBM utilization, which are presented in Figure 5. A summary of the simulation results are presented in Table 3. With a confidence interval of 95%, the total project duration time was between 854.87 and 862.84 shifts. The mean simulated project duration time is approximately 859 shifts, which is a little different from the real data (867 shifts) and close to the real project duration time (0.92%). The expected number of stoppages for cutting tools change is 11.14 (the real number is 11). Finally, the average simulated utilization factor is approximately 14%.

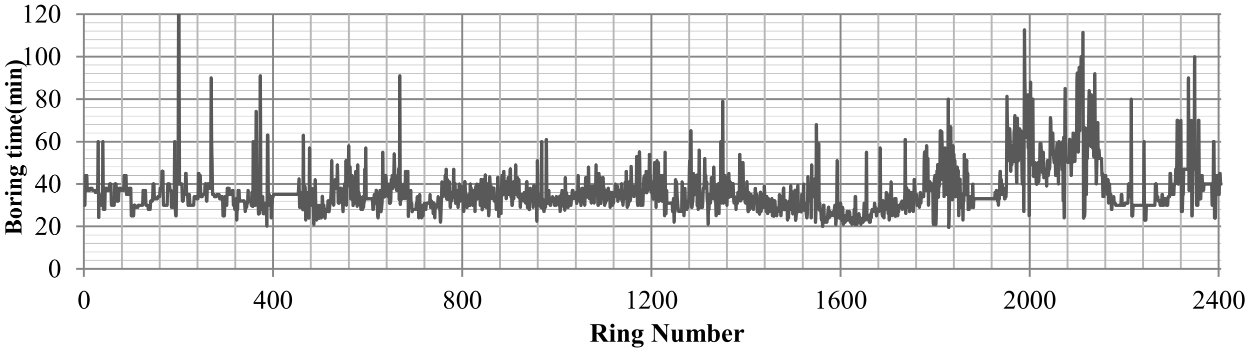



**Figure 2. Real boring time.**

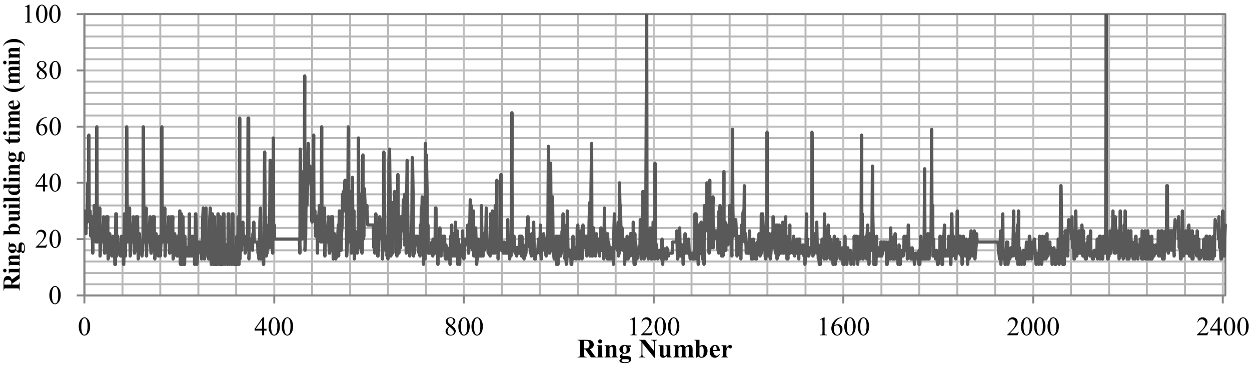



**Figure 3. Real ring building time.**

**Table 1. Best-fitted probability density functions for cycle activities of studied TBM.**

| TBM cycle activities (minute) | Best-fitted function | Parameters |
|---|---|---|
| Boring time | Log-Logistic (3P) | $\alpha$=3.9756 $\beta$=17.769 $\gamma$=16.368 |
| Ring building time | Lognormal (3P) | $\sigma$=0.62899 $\mu$=2.123 $\gamma$=9.0618 |
| General tunneling activity time | Log-Logistic (3P) | $\alpha$=2.3998 $\beta$=18.654 $\gamma$=1.0364 |
| Train delay time | Triangular | m=30; a=20; b=70 |

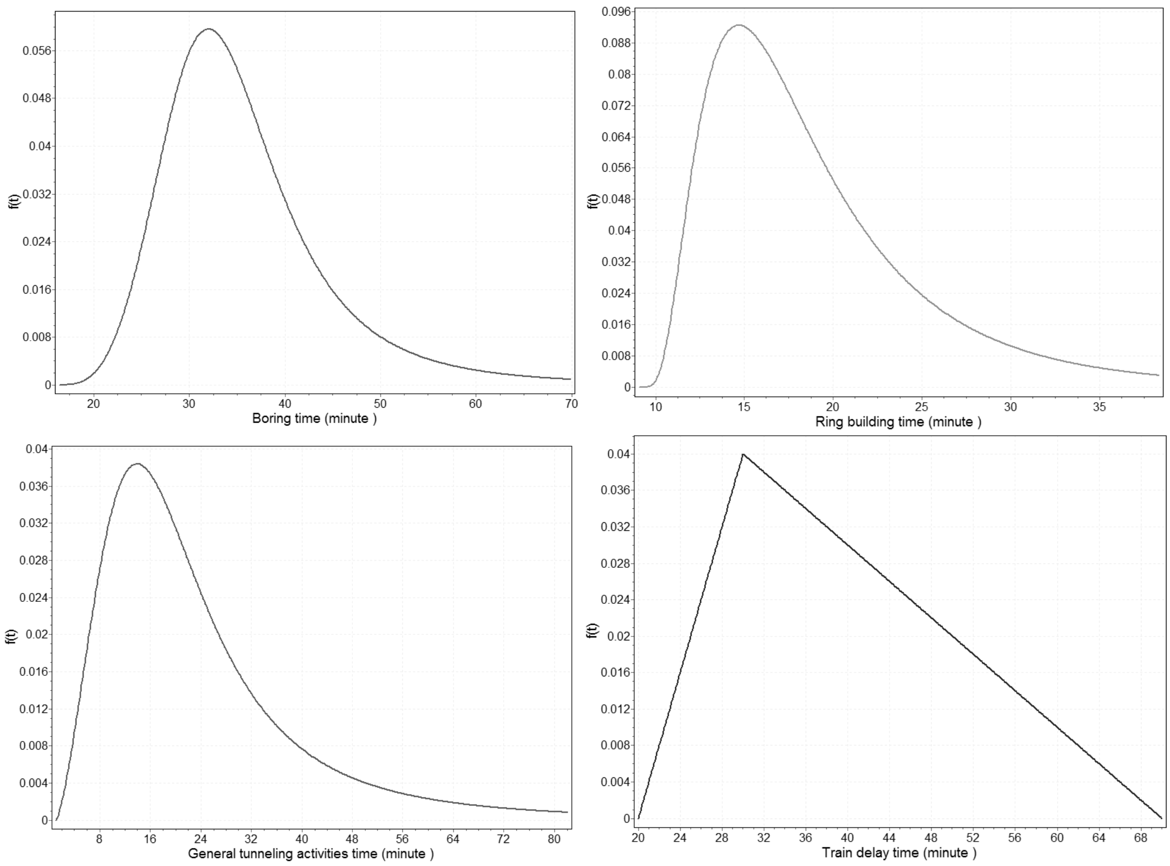



**Figure 4. Probability density function plot of TBM production cycle activities.**

**Table 2. Best-fitted probability density functions for RBS and TTR of studied TBM.**

| | Best-fitted function | Parameters |
|---|---|---|
| RBS (ring) | Weibull | α=1.549 β=274.91 |
| TTR (h) | Log-Logistic | α=2.013 β=105.11 |

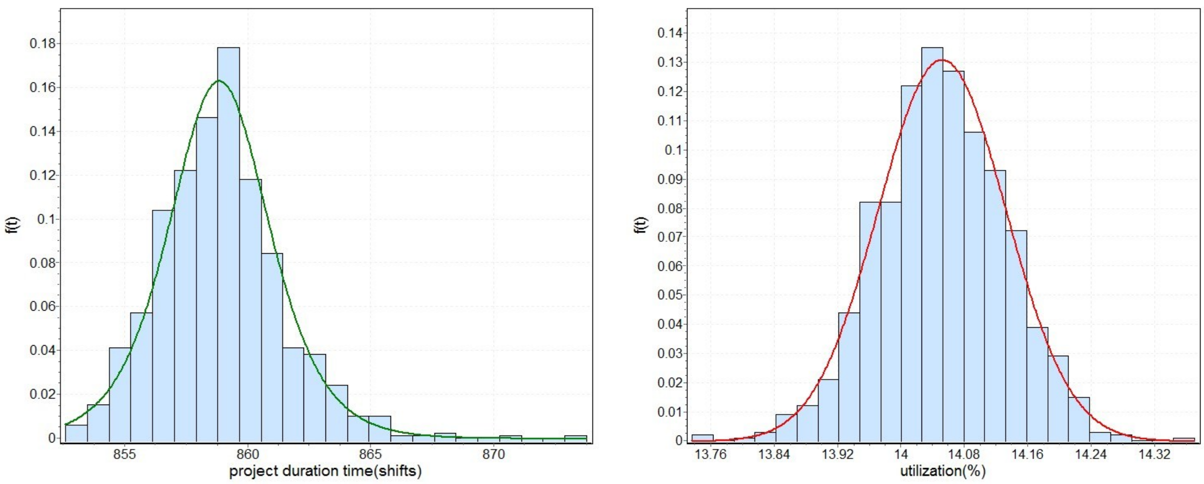



**Figure 5. Probability distribution for simulation of project duration and TBM utilization.**

**Table 3. Summary of simulation results.**

| | Mean | St. Dev. | Minimum | Maximum | Real |
|---|---|---|---|---|---|
| **Project duration (shift)** | 858.87 | 2.46 | 852.62 | 873.74 | 867 |
| **Utilization (%)** | 14.052 | 0.0804 | 13.736 | 14.370 | - |

Since this TBM will be used for excavation in line-3 of Tabriz urban railway as well, given the fact that both projects have similar geological and working conditions, in the next step, we used this method, and simulation was run for the next 5600 meter excavation of tunnel. The details of project duration time for line-3 is shown in Figure 6. This means that mechanized tunneling system utilization is heavily dependent on TBM and logistic system maintenance down times and muck removal system. By selecting a suitable maintenance strategy and the muck removal system (such as belt conveyor or proper use of California switch), the utilization could be increased considerably.

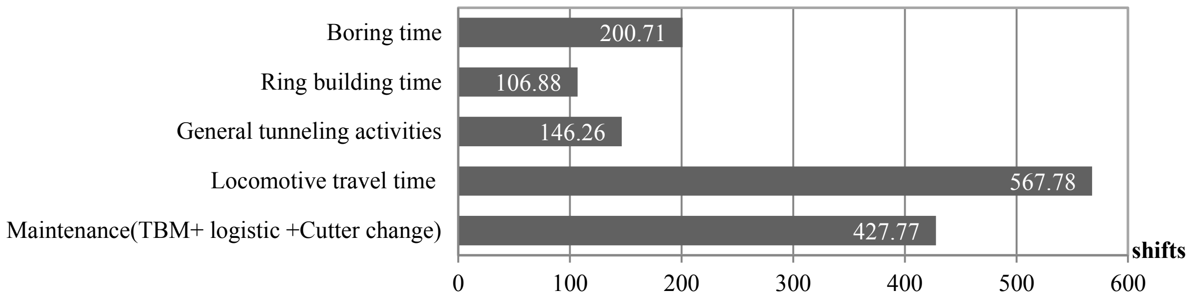



**Figure 6. Project duration time details for 5600 meters excavation of tunnel (total time: 1449.4 shifts).**

## 4. Conclusions

This paper presents an approach to simulate the mechanized tunneling process using the available historical data in a Tabriz underground train project. The performed Monte Carlo simulation reveals that the average utilization of TBM is 14%, which is dramatically low for such an expensive and high technology system. However, the resulting probability density function (histogram) shows that even lower utilizations have been recorded, and generally, the utilization varies from 13 to 15 percent. In addition, the mean simulated project duration time is approximately 859 shifts and close to the real data (0.92%). The presented approach shows that the utilization in a mechanized tunneling process is affected not only by the penetration rate but also by the maintenance strategies and material transportation or muck removal system type. Therefore, in the case study project, it is recommended to improve the current site arrangement, activity management, and work order generation system.

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# شبیه‌سازی بهره‌وری دستگاه حفاری تمام مقطع تونل: مطالعه موردی

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**چکیده:**

بهره‌وری یکی از مهم‌ترین عوامل مدیریتی است که در تجزیه و تحلیل فرآیند ساخت و ساز مورد استفاده قرار می‌گیرد. مقدار بهره‌وری به طور مستقیم بر روی مدت زمان کل پروژه و هزینه‌های نهایی ساخت تأثیر می‌گذارد. بنابراین، مطالعه بهره‌وری در پروژه‌های تونل‌سازی ضروری و لازم است. در پژوهش حاضر بهره‌وری دستگاه حفاری تمام مقطع تونل از نوع فشار تعادلی زمین که در پروژه تونل قطار شهری تبریز مورد استفاده قرار گرفته است، با به کارگیری شبیه‌ساز مونت‌کارلو مورد بررسی و ارزیابی قرار گرفته است. برای شبیه‌سازی، داده‌های مربوط به عملیات اصلی تونل سازی شامل زمان حفاری، زمان رینگ‌گذاری و زمان لازم برای حرکت سیستم حمل و نقل لوکوموتیو در طول هر شیفت کاری جمع‌آوری شد. علاوه بر زمان‌های مربوط به عملیات اصلی، زمان‌های توقف دیگر مانند زمان تعمیر و نگهداری دستگاه TBM و سیستم پشتیبان دستگاه، زمان تعمیرات سیستم‌های تدارکات موجود در داخل تونل و سطح زمین، زمان لازم برای جایگزینی ابزار برش و تاخیرات سیستم لوکوموتیو نیز جمع‌آوری شده و در شبیه‌سازی در نظر گرفته شد. نتایج شبیه‌سازی نشان داد که زمان لازم برای اتمام پروژه مورد مطالعه حدود ۸۵۹ شیفت کاری است و تفاوت بسیار کمی (حدود ٪ ۰/۹۲) با داده‌های واقعی دارد. در نهایت میانگین ضریب بهره‌دهی سیستم تونل سازی حدود ٪ ۱۴ تخمین زده شد.

**کلمات کلیدی:** دستگاه حفاری تمام مقطع تونل، بهره‌وری، شبیه‌سازی، زمان توقف.