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Mechanized tunnels lining prefabricated segments production methods

Elaheh Banihashemigargari*[1] and Amir H. Rezaeifarei[2a]

[1]*Master of Industrial management, Tabriz, Iran*
[2]*Department of Civil Engineering, Azarbaijan Shahid Madani University, Tabriz,35 km. of Maragheh Hwy, Iran*

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Abstract. In tunneling projects, a significant part of the costs is spent on segment production. By more economically producing, the cost of tunnel construction can be greatly reduced, especially in long and large-diameter tunnels. In the present study, the effect of using the Carousel method in the improvement of the production system performance compared to the conventional Static system has been studied. To carry out the research, a quantitative comparison of cost and production time was carried out for two production methods using the available documentation. The opinions of experts have been obtained using questionnaires and qualitative comparison of cost, time and production quality was done by implementation of statistical analysis. The SPSS software and the univariate t-test were used to analyze the questionnaires. According to the results of statistical analysis with SPSS, the use of the Carousel method will reduce production time and costs along with increasing manufacturing quality. According to the documentation analysis, the Carousel method reduces the cost of production by almost 30% and leads to a reduction of the production time to approximately 40% of the Static moulds system. The Carousel method has a higher production rate, efficiency, and better performance. Research into quantifying the benefits of Carousel method in the production system performance is very limited. This comparison is based on real information from the under construction Tabriz Metro project. This article can be very helpful in choosing the best production method.

Keywords: carousel method; cost and quality; prefabricated segments; production time, statistical analysis; Tabriz Metro

1. Introduction

With population growth and the expansion of cities, the need for infrastructure and urban highways is also increasing. Because of limitations of available space at the ground surface, high land acquisition cost, saving time and energy with shorter urban trips, increase safety and reduce environmental impact in addition to the increasing need for land, especially in densely populated areas of cities, the use of underground spaces and tunnel construction projects has increased dramatically in recent years. Especially in Iran tunnelling projects have increased rapidly, and in addition to the six metropolises in the country, many tunnel projects are being constructed or studied and designed in most major cities. There are several methods to tunnel excavation that can generally be divided into conventional and mechanized methods. In the conventional excavation method, the construction of the tunnel is carried out in several stages. Includes excavation, by using the drill and blast methods or very basic mechanical excavators, mucking, placement of the primary support elements and then execute the permanent tunnel lining. Due to the type of excavation carried out, conventional tunnel construction has been limited to the grounds with good stability and no groundwater and also is a time-consuming method (Hudson and Harrison 2000). Besides conventional excavation methods, shield tunnelling is now a well- stablished method which allows for tunnel excavation in different types of soils and difficult geological conditions such as high-water table, soft soils or low overburden. Due to its multiple advantages compared to the conventional methods and the ability of controlling surface settlements, the TBM (Tunnel boring machine) technology has been proposed as the most important tunnelling method of the last decades in urban areas (Rezaei and Ehterami 2019). Concrete segments are employed as lining system in tunnels, which are excavated by TBMs (Tunnel Boring Machines). In the mechanized excavation method, precast concrete segments are used to support the tunnel. These segments are placed next to each other to form a ring, these rings are connected to adjacent rings and form tunnel structures. The segments are fabricated in segment factories and transported to the tunnel for being installed by the boring machine (Guglielmetti *et al.* 2007).

These precast concrete segments are an economically significant part of tunnel construction. In the case of economical design and optimal production, the cost of tunnelling projects, especially long and large cross-section tunnels, will be significantly reduced. Up to now, numerous studies have been carried out to accurately evaluate the lining loads under different geotechnical conditions (Jalali and Beik 2018), which leads to an economical design of the lining; using various methods such as numerical modelling, physical small-scale modelling (Katebi *et al.* 2015), as well as a variety of analytical methods (Zhao *et al.* 2017). In addition to the economical design, the optimal and high-

*Corresponding author, MSc
E-mail: elaheh.banihashemigargari@gmail.com
[a]Associated Professor
E-mail: Rezaei.ah@azaruniv.ac.ir

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quality production of the tunnel lining segments can lead to a very significant reduction in the cost of mechanized tunnels. In addition to cost, the quality and production time of the manufactured segments are very important and effective factors in the timely completion and high-quality construction of tunnelling projects (Hariyanto *et al.* 2005). Regarding the production system of tunnel lining segments; Reichers (2014) summarized the precast concrete segments manufacture methods along with the production stages for each method. Piek (2014) also stated the innovations in the production of lining segments by considering various projects all around the world (Piek *et al.* 2014).

Fig. 1 Segment factory with Static Moulds

2. Segment production methods

The manufacture of precast concrete segments for tunnel lining is required to take place in a factory environment, in order that the different sequences of manufacturing may be carried out in a logical, pre-ordered, systematic process. The factory comprises of the production line(s), and storage areas. Basically, there are two methods of segment production – by using Static Moulds or a carousel system.

Generally, the steps taken to produce a concrete segment include oiling of the moulds, closing of the peripheral sidewalls, installation of reinforcement and inserts, closing of the covers and final checking, concreting of the mould, opening of the covers, smoothing of the extrados, closing of the covers and cleaning of the mould, curing, opening the mould and demoulding of the concrete segment with vacuum lifter.

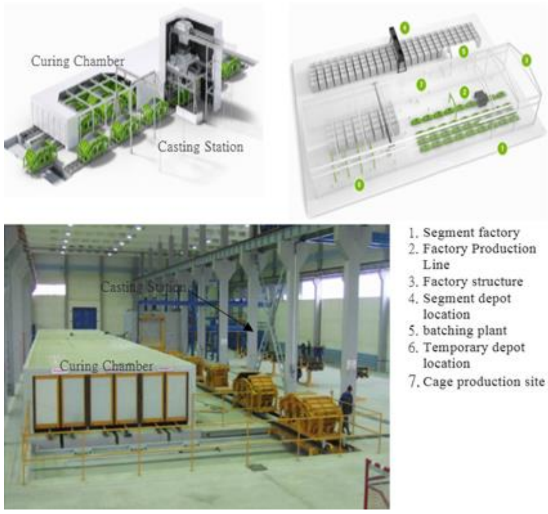


Fig. 2 Segment production factory with carousel system (https://www.herrenknecht-formwork.com)

2.1 Static moulds

In this system, a number of segment moulds are set up inside the factory shed in static positions. All components, including reinforcement cages, inserts and concrete, which are provided in other parts of the factory are moved to the location of the moulds. Prefabrication of the steel cages is done in jigs that are mould related in respect to shape, cast-in items and bolt inserts. These prefabricated reinforcement cages are lifted by cranes and delivered to the moulds. Concrete is transported from the batching plant in buckets carried by trucks or trolleys. At the casting yard, the buckets are lifted by overhead gantry crane before concrete is poured into the moulds. Concrete also can be delivered to the moulds by truck mixers or other wheeled delivery vehicles. During the placement of concrete, compaction is constantly applied by means of vibrators. Upon completion of casting, the upper surface is leveled and trowel Finished. After closing the covers and cleaning the moulds, the curing process is started by covering the moulds with insulating thermal blankets. Concrete segments are cured under certain conditions, known as accelerated curing, to give sufficient strength for demolding of the segments that in most cases is done by utilizing steam in the process. Due to the fixed location of the moulds, the piping must be made to steam to all the moulds. This needs more pipes and steam generation systems and boilers with more capacity. Once the segments achieve the required strength, they will be lifted from the mould using a vacuum suction equipment. In the final step, segments are turned 180º by means of the turning machine, and transported to the storage yard by transport cars. Fig. 1 shows an overview of a segment production plant with Static Moulds system. The main drawbacks of this production method are the need for more moulds, labor, machines or overhead cranes to deliver reinforcement cage and concrete to the moulds' location.

2.2 Carousel method

In this method, the concrete is placed in the moulds at a fixed station and the moulds are delivered to the casting station on a motorized circuit known as a carousel. The carousel circuit contains a number of full ring sets of moulds and the manufacturing is designed as an industrialized process comprising several workstations that each mould passes through on its journey around the carousel. Besides the casting, the curing process in this method is done at a fixed station within a curing chamber. Fig. 2 shows the general view of a segment factory of the Carousel method. It can be seen that the major difference between the two methods of production is that with Static Moulds the workforce moves and the moulds remain in place and in a carousel system the moulds move and the workforce remains in place.

In this method, the moulds are first cleaned and oiled and then moved to the precast steel bar cage placement section. At this station, the cages are placed inside the mould using a light hand crane (Fig. 3(a)). In the next step, after closing of the covers, the moulds are transferred to the casting station on the transfer platform and the concrete is cast into the mould directly from batching plant (Fig. 3(b)). The concreting of the moulds can take place inside a cabin, which eliminates the need for frequent cleaning of the factory floor. A to-and-fro movable hopper takes the concrete in the mixer and brings it to the mould placed in the concreting cabin (Fig. 3(c)).

In the next steps, the covers are opened and after smoothing the extrados and mould cleaning, the mould enters into the curing chamber (see Fig. 3(d)). The curing chamber dimensions and the speed of mould movement inside the chamber are depend on the required curing time and number of moulds. Finally, once the mould is exited from the curing chamber, the covers and peripherical sidewalls are opened and the segment is demoulded by a vacuum equipment and placed on the tilting machine (see Fig. 3(e)). After demoulding of the segment on its fabrication line, the concrete segment must be turned over by 180° to place the extrados on the inside (see Fig. 3(f)). At the end of the cycle, the turned segment will go on a conveyor for transportation to the pre-storage and storage yard (see Fig. 3(g)). In this stage, additional measures such as gluing the gaskets to the segment can also be performed (see Fig. 3(h)).

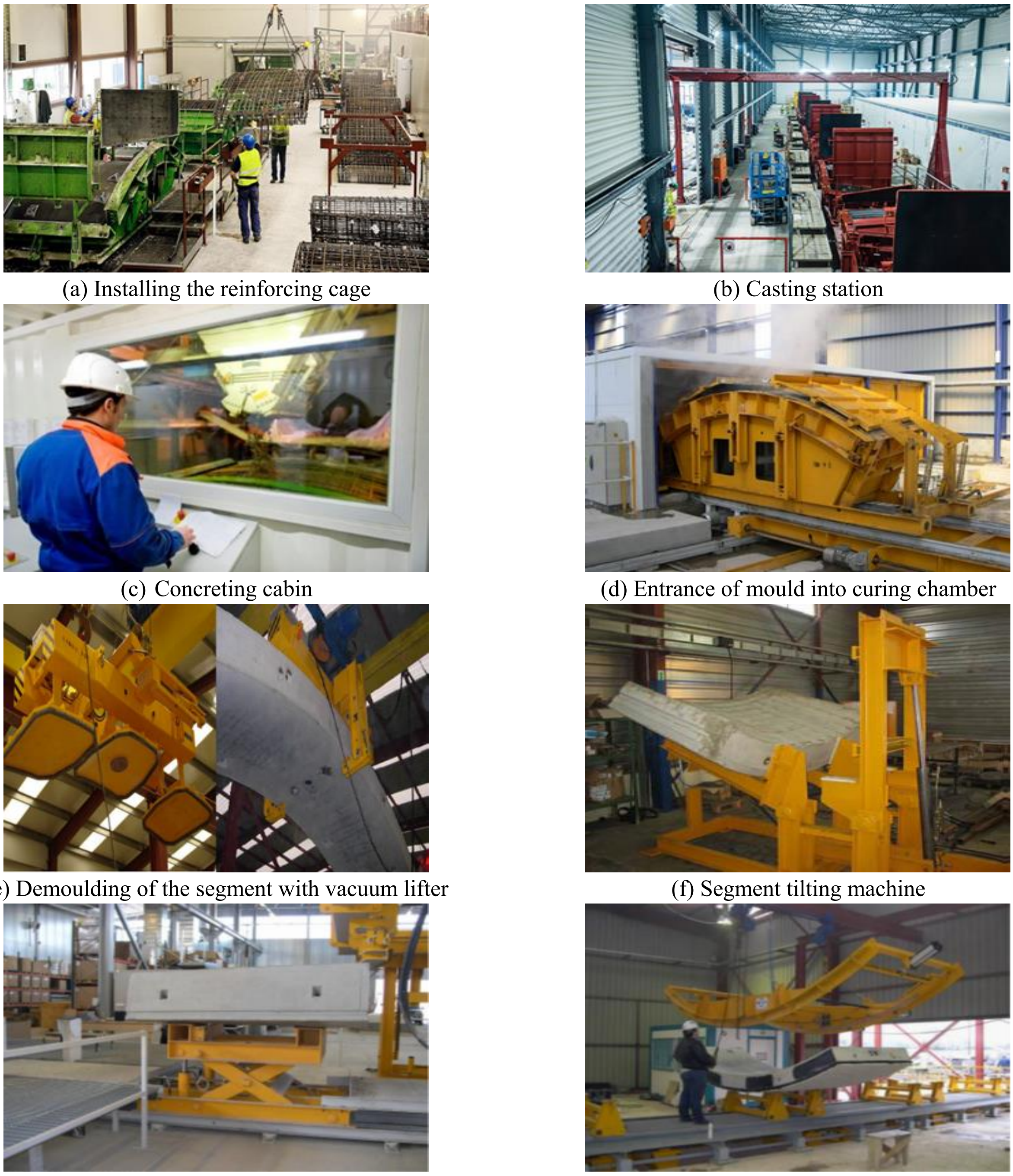
The process is typically controlled through programmable logic controllers (PLC) which can be integrated into the quality management system for segment manufacture, allowing a higher level of control and documentation compared to the Static Mould setup. It should be noted that due to carrying out the entire production process in fixed stations many of the disadvantages of the Static Mould system have been overcome. The transmission of reinforcing cages and concrete into the moulds is completely eliminated, resulting in a reduction of cost and time, QA / QC requirements and processes, as well as eliminating the risk associated with the handling of reinforcement cages. The production of segments is done in less time, lower cost and with high quality.

Choosing the best production method is one of the main issues to save costs and time of projects and improve the quality of the fabricated segments. The decision about which of these two methods is more desirable and cost-effective, depends on several conditions and factors, including the total number of segments, the tunnel diameter and length, the time schedule and the rate of production as well as local conditions. For example, in the Moscow metro project, the Carousel method has been more suitable than the Static system due to production time saving, need for less personnel, reduction of production costs, decrease in defective products and higher quality of segments. The application of Carousel system in the GKI tunnel project in Australia results in higher quality segments (due to the possibility of better control of the concrete and elimination of the effects of transport) with fewer damaged segments that were required repair. In addition, the concreting cycle was shorter so that one segment was manufactured each every 8 to 12 minutes (Riechers 2014). The CBE group mentions the following as the key advantages of the carousel method: significant productivity increase (up to 30 - 40%), increase in the production rate (one segment is produced every 7 to 10 minutes), less workers needed within the plant, safety increase, better segment quality, steady drying time (regardless of the weather), noise reduction since the moulds are isolated during the concreting phase (CBE Group).

Summarizing the above, it appears that the Carousel method is more suitable for use in tunnel projects and other underground spaces and will have higher performance. In a July 2015 newsletter, the German tunnel company, Herrenknecht presented a list of the most important projects implemented in recent years by the Carousel method, including metro lines in various countries all over the world. Due to the advantages of the Carousel method, the reception and use of this method in the world's metro projects is more than the Static Mould system. Considering the high volume of tunnel projects and the very significant cost of these projects, this issue's comprehensive study seems indispensable (Herrenknecht 2015). As mentioned above, choosing the production method for each tunneling project requires a particular and individual review based on the project's conditions. In the present case study of Tabriz metro, after an overview of existing production methods, the economic, temporal, and qualitative comparison of these methods has been conducted and the appropriate production method has been selected. Due to the multiple effective parameters in the field of production, in order to adapt to real conditions, the specifications of the Tabriz Metro Segment Factory have been used for research.

3. Research method and parameters studied

Performance of manufacturing systems covers a wide spectrum of technology and management activities. According to studies it is now generally accepted that it is necessary to measure all kinds of performance indicators, such as cost, speed, dependability, quality and flexibility (Hon 2005). In tunnelling projects, a significant part of the costs is spent on segment production. Production and supply of segments for tunnel construction projects have been studied from different aspects. (Ebrahimy *et al.* 2011). About precast concrete production process in the segment factory and its optimization various studies have been conducted. Purpose achieving project objectives in construction projects such as time, cost, and quality is a challenging task (Wang *et al.* 2021). In this paper, cost, time and quality, which are among the most important criteria for measuring system performance, are examined. This manuscript investigates the effect of the application of the Carousel method on the performance of the production system, considering the parameters of time, production cost and quality. As a case study the existing segment production factory of the Tabriz Metro and the specifications of its Line 2 tunnel has been considered.



(a) Installing the reinforcing cage

(b) Casting station

(c) Concreting cabin

(d) Entrance of mould into curing chamber

(e) Demoulding of the segment with vacuum lifter

(f) Segment tilting machine

(g) Segment evacuation line

(h) Gasket glueing

Fig. 3 Different steps of segment production in the Carousel method (https://www.cbe-tunnels.com)

To carry out the research, a quantitative comparison of cost and production time was carried out for two methods using the available documentation. Also, the opinions of relevant experts have been obtained using questionnaires and qualitative comparison of cost, time and production quality of the two methods was done by implementation of statistical analysis. In the first part, the time spent in each stage of production was determined for both methods and the total times of manufacturing were compared. For economic comparison, the main parameters affecting the cost of production, such as the cost of building the required space, supply of moulds, equipment, machinery, and labor were considered. In the second part, experts' opinions were obtained through a questionnaire consisting of 42 questions, which was prepared and compiled by the authors in collaboration with statistical experts. The questionnaire used a five-point Likert scale (very low, low, medium, high, and very high). Questions 1 to 15, 16 to 30, and 31 to 42 are related to the first, second and third hypothesis based on the effect of using the Carousel method in reducing production time, increasing product quality, and reducing production costs, respectively. The SPSS software and the univariate t-

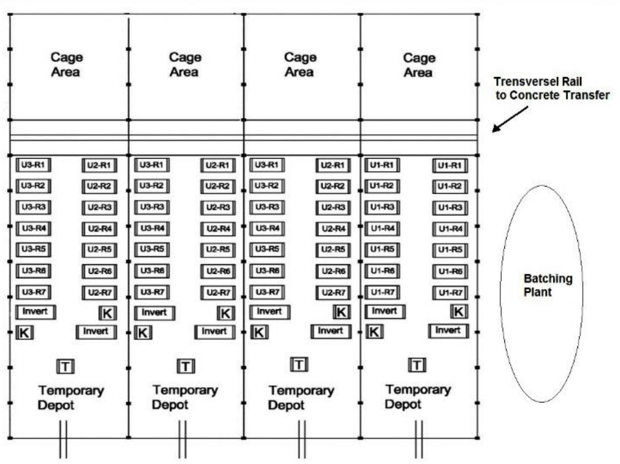


Fig. 4 The arrangement of moulds and other required spaces within the plant in the static mould system. (K: Key, T: Tippler)

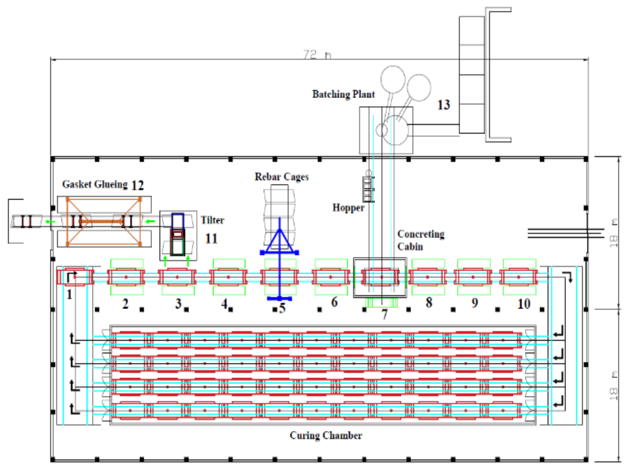


Fig. 5 A schematic considered plan of the Carousel method

test were used to analyze the questionnaire information.

4. Case study

The Tabriz metro segment factory has been built to produce the required segments in the Line 1 project. The Factory has an area of 52,000 square meters with an infrastructure area of about 7,000 square meters, including the office section and the production lines. The approximate area of the storage yard is about 20,000 square meters. The segment production part includes a 4-span industrial shed with dimensions of 18 × 72 meters in each span. There is one 10-ton overhead gantry crane on each span and Concrete mix is produced in the batching plant with production capacity of 30 cubic meters per hour. The production method for line 1 segments is Static Moulds method (Tabriz Urban Railway Organization). The present study aims to evaluate the feasibility of using all or part of the existing factory to produce the required segments of other lines of Tabriz metro. For this purpose, two methods of production (carousel and static moulds) were considered. The Tabriz Metro Line 2 project will be excavated as a single tunnel for approximately 22 km (Rezaei *et al.* 2019). Given the width of 1.5 meters per ring, around 14,700 rings will be needed to build the tunnel. Each tunnel lining ring consists of 9 segments, include 7 normal segments, 1 key and 1 invert. In order to choice of the best production method, the specifications of the production system for both methods were designed based on the production rate of 16 rings (144 segments) per day in two shifts and compared.

In Static Moulds method, 8 sets of metal moulds and a total of 72 moulds will be required. Fig. 4 shows a schematic illustration of the moulds arrangement and other required spaces within the plant.

As could be seen, in each span of shed 2 sets of moulds were considered. In the longitudinal direction, 3 span of 6 meters (area: 18×18 m^2) for prefabrication of the steel cages and storage of reinforcements was required. Also, the same area at the other end of each span was considered for tippler set and needed area for segments pre-storage after demoulding. The concrete is transferred from the batch to the factory with buckets on trolleys via transversal rails (see Fig. 4). The reinforcement cages and concrete are delivered to the location of each mould, as well as the segment is demoulded and delivered by overhead cranes.

In carousel method, the production system consists of 1 fabrication line (one mould waiting exit on production line transfer platform and 9 working station) and curing chamber. The required number of moulds for desired production rate was 54 and according to the curing time of 6 hours, the dimensions of the required curing chamber will be approximately 12 by 58 meters. Inside the curing chamber there are 4 curing lines with 11 moulds per line, which overall has a capacity of 44 moulds. A schematic plan of the fabrication line, working stations, moulds arrangement and curing chamber is illustrated in Fig. 5. The total required space for carousel method is about 72 by 36 meters (two sheds of 18m span).

According to Fig. 5 and the corresponding numbering, the segment fabrication line workstations include: Station 1: Mould waiting on transfer platform after finishing the curing; Station 2: Opening of the covers and peripheral sides; Station 3: demoulding of the concrete segment with vacuum lifter and placing on tilter (part 11 in Fig. 5) and after turning over by 180° to place the extrados on the inside, the turned segment will go on a conveyor for transportation to the pre-storage and storage yard (part 12); Station 4: cleaning and oiling of mould; Station 5: reinforcement; Station 6: completion of the works “released for concreting”; Station 7: Concreting of the mould and vibration of concrete, in this station, the mould may be placed inside a special concreting cabin and concrete is brought from the batching plant (part 14) by a to-and-fro movable hopper; Station 8: Stage of troweling and smoothing of the extrados; Station 9: Cleaning of moulds; Station 10: Waiting station to enter the curing chamber. In general, the mould stop time at each station is equal to 10 minutes. In other words, the fabrication rate will be 1segment/ 10 minutes, which is in agreement with the desired value.

5. Evaluate the effect of using the Carousel method through a questionnaire

In the literature there are a few papers that address evaluation of the performance of TBM in different scopes (Hamidi *et al.* 2010). Segmental lining is the main task of TBM that can increase the reliability of a tunnel – if done properly. The quality of the segmental lining is a main area within the performance of TBM. Generally, the concrete segments are subjected to several damages in each and every sequence of the four steps, beginning with manufacturing at the factory, transporting to the tunnel, installation at the tunnel and serviceability stage. Some researchers study the induced damages in each of these 4 steps, for instance (Hosseininasab and Ershadi 2015) and (Tajik *et al.* 2015) evaluate performance of the TBM in the scope of the quality of the installed rings. The nature of the damages, which take place on the parts while being produced and transferred are those, which could be reduced considerably by presenting a careful quality control system along with an appropriate mixing design and curing method. Suitable quality control methods have been discussed in some papers (Gruebl 2006). For fabrication of standard precast concrete segments, seven inspections are needed during various steps (ITA 2000).

In this part, the experts' opinions have been obtained using a questionnaire consisting of 42 questions and qualitative comparison of cost, time and production quality of the two methods was done by implementation of statistical analysis. Based on literature review and the field studies conducted in various projects, damages occurred in the concrete segments at production stage can be, generally, categorized to two major sources of improper concrete production and operational errors (operator's mistake). About the quality of manufactured segments, the questionnaire includes questions about the various possible damages such as crack and chipping of concrete segments, dimensional tolerances of segment, improper dowel nut insertion, improper finishing, absence of hanging sockets, imperfect geometry of steel cage, honeycombing, bleeding, broken gasket grooves and etc. (Shayanfar *et al.* 2018)

In the present study, to get adequate answers to the questions about production process (technical, temporal and qualitative details), the Tabriz metro segment factory, which has 75 employees, was adopted as statistical population. Cochran's formula, has been used to determine the population size.

$$n = \frac{\frac{z^2pq}{d^2}}{1 + \frac{1}{N}\left(\frac{z^2pq}{d^2} - 1\right)} = \frac{\frac{1.96^2 \times 0.5 \times 0.5}{0.05^2}}{1 + \frac{1}{75}\left(\frac{1.96^2 \times 0.5 \times 0.5}{0.05^2} - 1\right)} \cong 63 \quad (1)$$

Number of 63 questionnaires were distributed among the statistical population. 60 filled answer sheets were returned and, hence, the final evaluation was performed on 60 samples. Production time and cost reduction variables, with 60 samples and applying One-Sample T-Test were analyzed. Test results are presented in Table 1. According to the table, for production time and cost reduction variables, the standard deviations were 2.86 and 5.80, the t statistic values were 29.87 and 13.96, respectively, and the corresponding degree of freedom for the test was 59. Furthermore, the obtained Mean Difference values were 11.06 and 5.53, with upper bound of 11.80 and 6.12 and lower bound of 10.32 and 4.87, respectively, in 95% Confidence Interval. The average obtained for the production time and cost reduction variables were 56.06 and 20.53, respectively, which were higher than the Test Value 45 and 15. Hence, there is a significant relationship between the Carousel method and the production time and cost reduction. It can be concluded that the use of the Carousel method has a positive effect in reducing the production time and cost.

Table 1 One-Sample T-Test results

95% Confidence Interval		Mean Difference	Test Value	Mean	Std Deviation	df	t	N	
Upper Bound	Lower Bound								
11.80	10.32	11.06	45	56.06	2.86		29.87		Time
3.86	2.97	3.79	90	93.79	3.93	59	14.87	60	Quality
6.12	4.87	5.53	15	20.53	5.80		13.96		Cost

Similarly, for the quality improvement variable of segments, the standard deviation was 3.93, the t statistic was -14.87. Furthermore, the Mean Difference was 3.79 with Upper and lower Bound of 3.86 and 2.97, respectively, in 95% Confidence Interval. The average obtained for the quality improvement variable of segments is 93.79, which was higher than the Test Value=90 and it can be stated that there is a significant relationship between the Carousel method and precast concrete segments quality improvement.

6. Evaluate the effect of using the Carousel Method through project documents

6.1 Production time

To compare production time in two methods, the production scheduling documents have been used. In the Static Moulds system, that segment moulds are fixed in place, to produce each segment, machinery (overhead crane, etc.), components (precast steel cages, prepared concrete, etc.) and workers must move to the location of each mould. This takes a lot of time. For example, in the Static Mould system, after cleaning and lubricating the first mould, worker with the necessary tools must deployed to the second mould and this cycle repeats until all the moulds in one set are completed. The overhead crane transports the cages from the storage area to the first mould. The crane is then returned to the storage area and the second cage is delivered to the second mould. In each set, according to the number of moulds (which is 9 in the case study), the overhead crane performs a reciprocating motion along the factory. This issue increases the time of production compared to the Carousel method. The same steps are repeated to concrete each segment, and after curing, to lift and transport each segment. Due to the limited overhead cranes at each span, there will be a long waiting time, which will prolong the production time.

Table 2 Comparison of a ring segments production stages scheduling in the Static Mould system and Carousel method

Carousel method		Static Mould system		
Time (min)	process	Time (min)	process	Step
10	Waiting	10	Cleaning and Oiling of the moulds	1
10	Opening of top doors and holders	10	Cage placement	2
10	lifting and tilting the segment	10	Closing of the top doors	3
10	Cleaning and Oiling of the moulds	80	Waiting time for completion of cage placement for all moulds by overhead crane	4
10	Cage placement	15	Concreting of the mould	5
10	Closing of the top doors	10	Smoothing of the extrados	6
15	Concreting of the mould	10	Closing of the top doors and cover the mould by thermal blankets	7
10	Smoothing of the extrados	10	Picking up the covers and Opening the top doors and holders	8
10	Cleaning the moulds	10	lifting and tilting the segment	9
10	Waiting, The mould enters into the curing tunnel	80	Waiting time for completion of demoulding for all moulds by overhead crane	10
105	Total	245	Total	

In the Carousel method, workers are in a fixed place at each of the workstations. Machinery and equipment are in a fixed location and only moulds move on the platform and stop at each station, and after completing the corresponding production process, they move to the next stations. Hence, the cage placement, concreting and lifting stages can be done simultaneously and without any need for overhead crane movement.

The curing time in both methods is the same and equal to 440 minutes. Regarding the concrete curing, it is necessary to take into account a stay in the curing tunnel of 440 min (Number of moulds 44 x 10 minutes = 440 min). The difference in the curing process that can be mentioned, is the required labor and time related to covering the moulds by thermal covers for steaming and then picking them up by personnel in the Static Mould production method, which has been eliminated in the Carousel method. In the carousel method, the curing of 44 moulds is done simultaneously in curing chamber that leads to more uniform curing of segments and also reduces energy consumption and its loss via steam system pipes. Comparison of a ring segments production stages scheduling in the Static Mould system and Carousel method is presented in Table 2. Time values in Table 2 are based on in-place measurements for the Static Moulds system.

According to the results of Table 2 and the time required for each production Method, the total production cycle time (without curing) in the Static Mould system is 245 minutes and in the Carousel method is 105 minutes, which shows the reduction of the production time in the Carousel method to approximately 40% of the production time in the Static Mould system. It should be noted that according to the production rate of one segment every 10 minutes in the Carousel method, 144 segments can be produced in two 12-hour work shifts. (16 ring per day). Given the curing time and the placement of the two sets of moulds in each span, this production rate isn't achievable in the Static Moulds system and requires adding one extra overhead crane in each span and/or concreting the moulds using truck mixers. It will increase the cost as well as many executive problems.

6.2 Production cost

According to studies, the main problems of the current production process are related to equipment, technology and organization (Wang *et al.* 2020). The most important influence factors in the cost of production include the construction of different parts of the factory, the supply of the necessary moulds, the equipment used, the machinery and the labor. Carousel systems provide a factory production line process and will normally require a lesser number of labor and segment moulds than a static system and may also require a smaller factory footprint. In this system, the number of workers on the production line has been reduced from 20 to 12 person per shift, which has a direct effect on production costs, including wages, etc. The number of workers needed to transport supplies to the moulds, as well as the delivery of manufactured segments to the storage yard (for example, overhead cranes operators in

Table 3 Production quantities and related costs of labor for Static Mould system and Carousel method

Description	Static Mould system	Carousel method
The total number of lining rings of Tabriz metro project	14700	
Unit cost / hour (€)	2	
Production rate	16 Rings per day	16 Rings per day
Number of moulds sets	8	6
Number of moulds	72	54
Manpower required for each shift	20	12
12 hours (Working shifts)	2	2
Amount of daily production (number of segments)	144	144
Production rate (segment / manpower / day)	3.6	6
Estimated cost of manpower for a ring (€)	60	36
Estimated total cost of manpower for the project (€)	882000	52920
Difference in labor cost for two methods (€)	882000-529200 =352800	
Number of segments manufactured per mould set	1837	2450

Table 4 Main cost components of Static Mould system and Carousel method

Cost of items related to the production line (€)		
Description	Static Mould system	Carousel method
Moulds	1332000	999000
Carousel System components	-	397000
Mould lifting equipment (clamps, etc.)	81000	81000
Installing production line	125000	125000
Design and assembly	41500	100000
Transportation	128000	112000
total costs	1680500	1814000
Cost of equipment, ancillary facilities and construction of required buildings (€)		
Required factory area	72×72 m =5184 m2	72×36= 2592 m2
Area required for depot of cages and segments	included	16×50 = 800
Additional cranes (4 × 18-meter-span 10-ton overhead cranes)	260000	-
boilers, plumbing and covers	180000	included
additional area (2592 square meters)	388800	-
Depot area (800 square meters)	-	120000
Total equipment costs	2509300	1934000
The difference between the total cost of the methods	1934000-2509300=575300	
the total cost		
Total manufacturing cost (Labor, supply, equipment…)	3391300	2463200
Reduction of total Carousel method compared to Static Mould system	352800+575300 928100=	
Cost reduction in Carousel method (%)	28	

each span) will be reduced. Also, fewer workers for cleaning, lubrication, installation of buried parts, opening and closing of moulds doors, troweling the concrete surface after concreting, and curing will be required.

For the given daily production rate of the 16 rings per day, a total of 144 segments should be manufactured per day, of which 72 pieces are destined for each shift.

According to the number of workers on the production line and the division of 72 segments by the number of workers, in the Static Mould system and the Carousel method, 3.6 and 6 segments are produced per person, respectively. This indicates a higher production efficiency in the Carousel method. Table 3 compares the labor costs in two production methods. The number of people and the work shifts are based on the expected production rate. According to the results, the application of the Carousel method will reduce the labor cost for the selected project by 40%. It should be noted that the total cost of manpower obtained is based on the considered unit price, and by increasing this amount, the cost difference between the two production methods will increase.

Table 4 provides a general comparison of equipment costs and required spaces for the two production methods. It can be seen that the Carousel method has approximately 23% lower equipment and construction costs and considering the difference in labor costs, in total, there is a reduction of approximately 28% in costs in the Carousel method compared to the Static Mould system.

Considering the production stages time schedule, in the Static Mould system and Carousel method, 72 moulds (8 sets of moulds) and 54 moulds are required, respectively, to reach the production of 16 rings per day. Thus, Static Mould system has a higher cost in terms of mould supply. In the Static Mould system, the required space for manufacturing (include production lines, precast reinforcement cages preparation, and temporary storage area) is 5184 square meters. The required factory area for the Carousel method is a total of 3392 square meters (Table 4). Hence, the required area in the first method is about 1800 square meters more than the Carousel method, which imposes more cost of land acquisition and construction of more building on production.

7. Conclusions

Due to the advantages of the Carousel method the acceptance and use of this method in metro projects around the world is increasing. In the present study, the effect of the application of the Carousel method on the performance of the manufacturing system has been investigated considering the parameters of production time, cost, and quality. As a case study the existing segment production factory of the Tabriz Metro and the specifications of its Line 2 tunnel has been considered. To carry out the research, a quantitative comparison of cost and production time was carried out for conventional Static Mould system and Carousel method using the available documentation. Also, using questionnaires a qualitative comparison of cost, time and production quality of the two methods was done by implementation of statistical analysis. The important results are as follows:

According to the results of the questionnaire analysis, the average obtained for the manufactured segments quality improvement variable was 93.79, which is higher than the Test Value=90. It shows the effect of using the Carousel method in increasing the quality of the manufactured concrete segments. Due to the lack of a Carousel method plant in the country, field information is not available and the comparison of two methods was done through the opinion of experts by statistical analysis.

Based on the results of the statistical analysis, the average obtained for the production cost reduction variable was 20.53, which is higher than the expected average of 15.

It can be concluded that the use of the Carousel method has a positive effect in reducing the production time and cost. Also, based on documentation, the use of the Carousel method will reduce the labor costs by 40% and equipment and construction costs by 23%. In total, for the selected project, there is a reduction of approximately 28% in costs in the Carousel method compared to the Static Mould system.

According to the results of Table 2 and the time required for each production Method, the total production cycle time (without curing) in the Static Mould system is 245 minutes and in the Carousel method is 105 minutes, This indicates the reduction of the production time in the Carousel method to approximately 40% of the production time in the Static Mould system. Also, the manufacturing rate in the Carousel method is considerable and more than the conventional static moulds system and the production rate of one segment every 10 minutes is achievable. Whereas, for the adapted case study, this production rate isn't achievable in the Static Moulds system. The obtained results of the questionnaire is in line with this. The average obtained for the production time reduction variable was 56.06, which is higher than the Test Value=45. Therefore, with 95% confidence, it can be stated that there is a significant relation between the applying Carousel method and reduction in production time.

Based on results and considering the various mentioned benefits, The Carousel method is recommended in the executive, technical and economic spheres in future mechanized tunnel projects in the country. It should be paid special attention to the Carousel method in projects which are in the design stage. By building a production plant in a carousel method, after completing the construction of the concrete segments of the relevant project, it is possible to set up a production line of concrete parts with different dimensions and different applications by changing the moulds.

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