Track Management Approaches for Underground Tunnel Construction

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Abstract

The evacuation of muck and transportation of material and equipment within underground tunnels under construction are usually performed using so-called supply trains. Managing the movement of several incoming and outgoing trains on a rail track, designated in this paper as "track management", is therefore essential to the success of tunnel construction. This research studied two different approaches to track management by using a sizeable drainage-tunnel construction in Bangkok as a case. Petri Net-based models were developed, and COSMOS simulations were performed to gain insight into the two different approaches to track management. The results indicated that the first approach, a rather general one, is easy to manage. However, this approach is prone to an operation-deadlock problem if there is a lack of balance between the number of trains and the number of double-track points along the rail track. The second approach was found to be more complicated to operate but had no deadlock issue. The second approach, therefore, provides flexibility in managing the track, as it allows more combinations of the number of supply trains and the number of double-track points.

Keywords: Track Management; Underground Tunnel Construction; Modelling; Simulation; Petri Nets; COSMOS

1. Introduction

A 9.4 km long tunnel with an inside diameter of 5 m is being excavated in Bangkok, Thailand using tunnel boring machines (TBM). The tunnel is an integral part of the drainage system, intended to lessen the flooding problem in the eastern area of the city. The construction cost of the entire project is approximately 155 million USD. Supply trains containing muck cars are employed for the muck evacuation process during the TBM boring. The supply trains are also used to transport the segments for the tunnel lining from the tunnel shaft to the TBM. The operation of the supply trains must then be synchronised with that of the TBM. The most extended portion of the tunnel without a vertical shaft for muck disposal is 5.5 km, considered very long. Several trains for the evacuation of

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muck and the transportation of material and equipment are thus required. Managing the movement of several incoming and outgoing trains on a rail track, referred to in this paper as "track management", is therefore essential to the success of the tunnel construction.

This paper presents the study on track management by applying two different track management approaches to the underground-tunnel construction operation. The results indicate the advantages and disadvantages of the two methodologies, which will be discussed in this article.

2. Methods

Petri-Net based modelling and simulation approaches were implemented in this study. Petri Nets are a widely accepted modelling methodology that has been being used in various domains. Apart from construction and civil engineering, Petri Nets have been studied and applied in several areas or topics including integrated manufacturing system (Zhang and Anosike, 2012), distributed manufacturing process (Lv *et al.*, 2013), Biological networks (Chen *et al.*, 2011), preventive maintenance (Roux *et al.*, 2013) and business processes (Si *et al.*, 2018). In construction and civil engineering, Petri Nets have been applied to some construction processes or topics such as earthmoving operation (Wakefield and Sears, 1997), gantry crane operation (Singh *et al.*, 2017), and quality assurance and efficiency analysis (Rinke *et al.*, 2017). However, no publication related to the application of Petri Nets on track management for tunneling operation was found.

In this research, Petri Net- based models for the tunnel boring operation were created. The models were then simulated using the COSMOS simulator, which is the software for running Petri Net-based models or COSMOS models. The simulator was developed by the author's research team based on the COSMOS system (Construction Oriented Simulation MOdelling System) (Damrianant, 2003), which is an extension of Petri Net methodology, including the software for running simulation.

2.1 The Tunnel Construction Process

Each TBM used in the excavation operation is divided into two main parts, i.e. a shield body and a back-up system (see Fig. 1). The shield body is in direct contact with the soil and the cutting face. There is a cutter head on the front of the shield body. The other main part is the back-up system which is the rolling portion that follows the shield. It carries all the accessories to allow the continuing advance of the TBM. To follow the shield body, the back-up system needs to move on a railroad track having particular rails of its own, which are separated from the rails for the supply trains (see Fig. 2). (TERRATEC, 2016)

The rails for the supply trains in this project constitute a single railway track, allowing only one train to pass at a time. However, there are double tracks at specific points along the railway track. A double-track point consists of two single railway tracks, where two trains going in opposite directions are allowed to pass, or they can each park on one of the single tracks at the same time. Fig. 3 shows the single railway track and a double-track point.

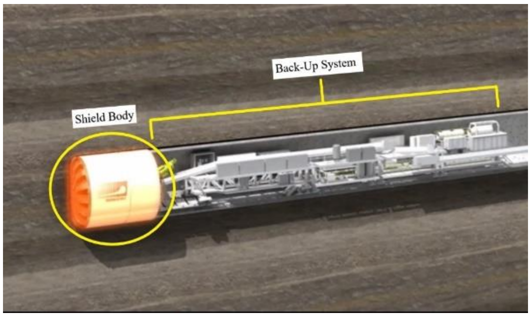

Fig. 1. Two main parts of TBM: shield bodyand back-up system (Screenshot from TERRATEC (2016))

Fig. 2. Rail tracks for supply trains and back-up system

Fig. 3. Single railway track and double-track point

A supply train used in this project comprises 2 segment cars, 1 locomotive, 6 muck cars and 1 flat car. Three activities related to the supply trains are performed within the back-up system as follows:

2.1.1 Evacuation of soil: The muck, which is the excavated material that results from the excavation of the cutter head of the TBM, is transferred from a crew conveyor to a belt conveyor. The muck is then dumped into muck cars, which are a part of a supply train. The train subsequently transports the muck to the nearest tunnel shaft where a vertical transportation system lifts the muck to the surface level for disposal.

2.2.2 Conveyance of segments and other supplies: The segments for the tunnel lining and other supplies, which allow the advance of the TBM, are transported to the back-up system using the supply trains.

2.2.3 Relocation of rails: Two rails, 6 m each, at the back of the back-up system must be relocated at a certain point in time to allow the advance of the back-up system.

The lining of the tunnel is composed of pre-cast concrete segments. The installation of the segments is performed by equipment called the erector arm, which is located at the rear body of the shield. Once the TBM has completed the excavation for 1 ring, the erector commences the installation of the segments. The TBM installs one ring after another, which allows the tunnel length to increase until the construction of the tunnel is finished. (TERRATEC, 2016) In this project, a ring of the tunnel lining is composed of 6 segments. The excavation for 1 ring causes 40 m3 (loose volume) of muck. One kilometre of the tunnel lining consists of 900 rings, approximately.

When a supply train arrives at the TBM, it stops at the front part of the back-up system at the back of the shield body and begins several activities within the back-up system unit.

For every 4 rounds of the supply trains coming in the back-up system, other materials apart from the segments are carried by the trains on the flat car. The materials comprise 6 m long rails for the extension of the rails for the supply train itself, pipes and other accessories. When the train arrives at the back-up system and is at the desired position, those materials are transferred to the back-up system using a crane called the primary host.

For the TBM, a cycle of its operation comprises 2 main activities, i.e. the soil excavation and the installation of the segments for 1 ring. The cycle commences from the excavation and finishes when 1 ring of the tunnel lining is installed.

Two rails, 6 m each, at the back of the back-up system must be relocated for every 10 rings installed. The rails will be removed from their current positions and reinstalled at the head of the track, which is near the rear of the shield body. The relocation of the rails will allow the continuing advance of the back-up system.

The readers can consult Damrianant (2018) for more details on the segment installation and other activities within the back-up system.

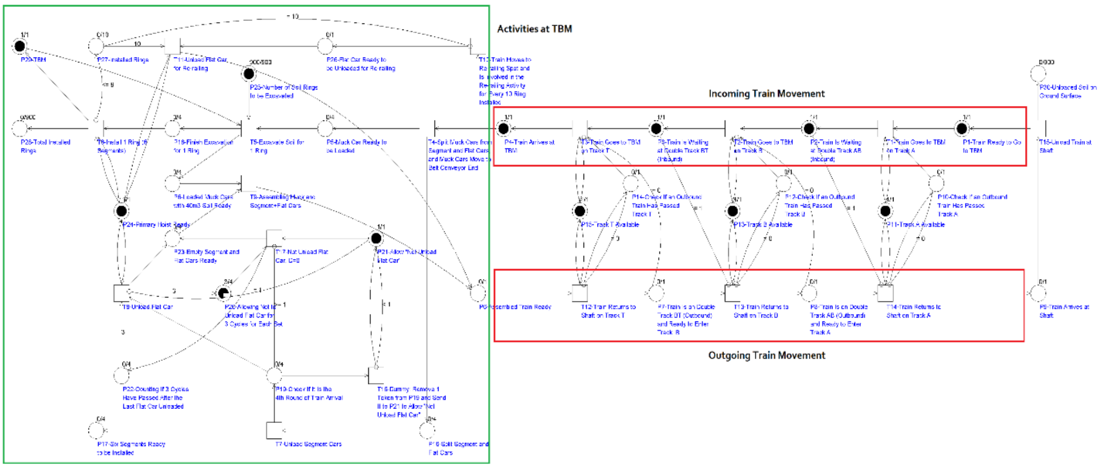

Fig. 4. PN-based model of the whole tunnel construction and excavation process with track management Approach-1

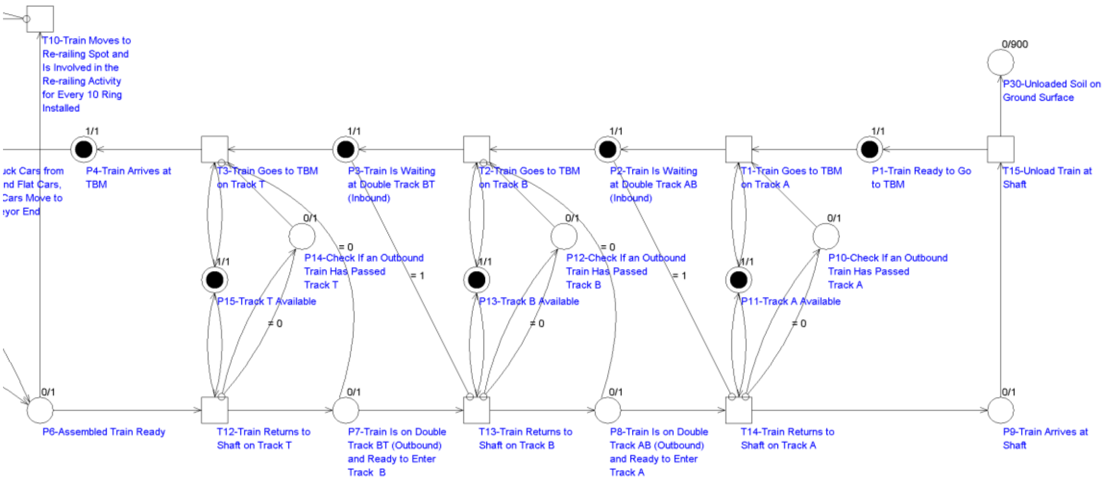

Fig. 5. Partial model illustrates the movement of supply trains under Approach-1's rules.

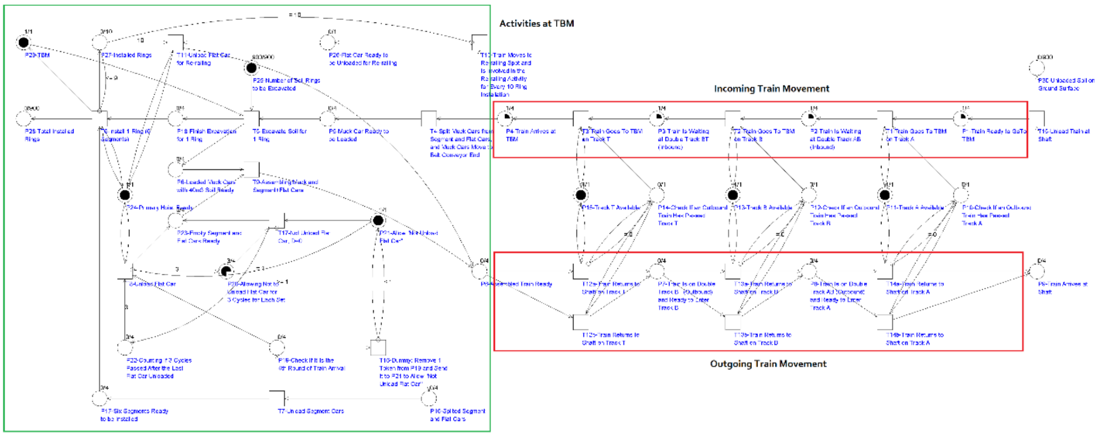

Fig. 6. PN-based model of the whole tunnel construction and excavation process with track management Approach-2

2.2 Track Management Approaches

Two track-management approaches for the movement of the supply trains were studied, referred to as Approach-1 and Approach-2.

The principle of Approach-1 is that both incoming and outgoing trains must meet at a double-track point before they can leave or pass the point. Approach-1 then uses the following rules. An outgoing train (the train driving from the TBM to the shaft) can pass a double-track point if and only if there is an incoming train parked at the point. Otherwise, the outgoing train must wait at that point until an incoming train reaches it. Once the incoming train has arrived at that point, the outgoing train can move forward to the next double-track point. Fig. 4 displays a PN-based model of the whole tunnel construction process using track management

Approach-1. The left portion of the model represents various activities performed at the TBM. Fig. 5 illustrates the right part of the model, which represents the movement of supply trains on both inbound and outbound tracks under the rules of Approach-1.

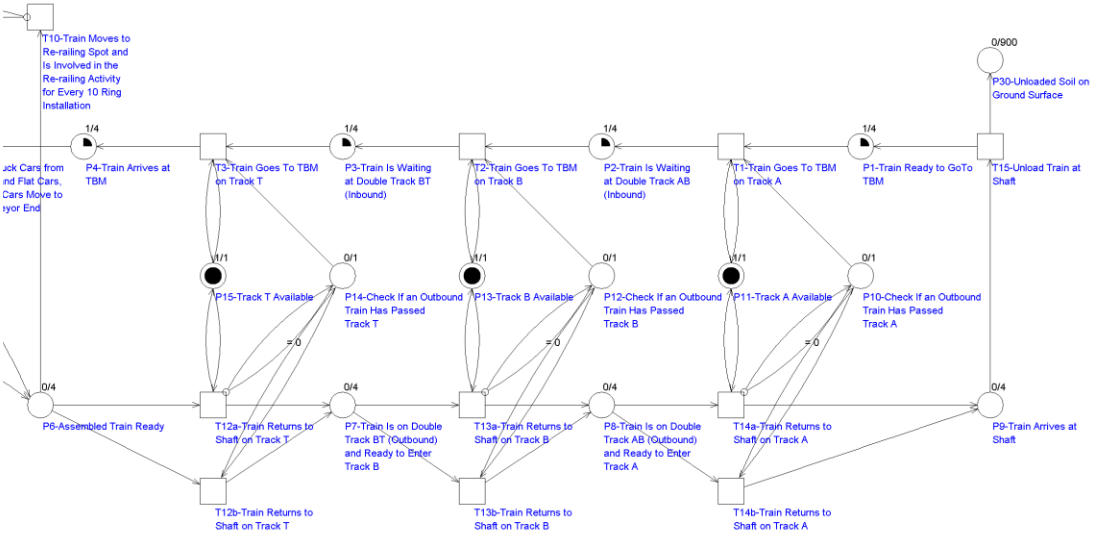

Fig. 7. Partial model illustrates the movement of supply trains under Approach-2's rule

The track management rule of Approach-2 is that outgoing trains have higher priority than that of incoming trains. If any track interval (a portion of single railway track between two adjacent double-track points) is vacant, i.e. there is no train on it, an outgoing train will use that track. However, an incoming train cannot use or pass any vacant track interval unless at least one outgoing train has passed that track interval. In other words, an incoming train is allowed to leave a double-track point on which it is parking when and only when at least one outgoing train has passed the next track interval of the double-track point towards which the incoming train is heading. However, the outgoing train does not need to pass that track interval when the incoming train is parked at the double-track point, but the outgoing train may have passed the track interval before the incoming train reaches the double-track point. Nor is there a requirement that the outgoing train will be allowed to pass the double-track point if and only if there is an incoming train parked at that point. This means that the outgoing train can pass a double-track point even if no incoming train at all is parked at that point. Fig. 6 displays a PN-based model of the whole tunnel construction process using track management Approach-2. Fig. 7 shows the right part of the whole model, which represents the movement of supply trains on both incoming and outgoing tracks under the rules of Approach-2. It should be noted that all activities performed at the TBM for the

Approach-2 case are the same as those for Approach-1.

2.3 Tunnel-Construction Process Models

Petri Net-based models for the underground tunnel construction for both approaches of track management were developed. The main models were adjusted into several models to represent the cases where the tunnel lengths are extended from the advance of the TBM. The tunnel lengths in the models mean the lengths from the shaft to the furthest position at the front part of the back-up system where the supply trains are. However, the model presented in this paper will be for the case where the tunnel length is 5.5 km, and two double-track points are along the railway track from the shaft to the TBM. Table 1 provides the cases for modelling and simulation. These cases differ by the tunnel lengths, the number of the double tracks along the lengths and the number of the supply trains used. Fig. 8 illustrates the track layout of cases 1, 2, 4 and 10 from Table 1. All models previously shown in Fig. 4 to Fig. 7 are from case 4 of Table 1.

Table 1 Cases for tunnel construction model

Cases	Tunnel Lengths (km)	Number of double-rack points	Number of Supply trains
1	5.5	3	4
2	5.5	3	3
3	5.5	3	2
4	5.5	2	4
5	5.5	2	3
6	5.5	2	2
7	4.5	3	4
8	4.5	3	3
9	4.5	3	2
10	4.5	2	4
11	4.5	2	3
12	4.5	2	2
13	3.5	2	4
14	3.5	2	3
15	3.5	2	2
16	2.5	2	4
17	2.5	2	3
18	2.5	2	2

The durations of the activities of the tunnel boring operation, which include excavation, muck evacuation and segment installation, are given in Table 2.

3. Results and Discussions

The simulation results from the COSMOS simulator for the cases shown in Table 1 are summarised in Table 3 and Table 4, which are the cases for Approach-1 and Approach-2, respectively. The screenshot in Fig. 9 illustrates the COSMOS simulator's interface when the model for case 4 of Approach-1 is being run. Fig. 10 shows the same model when its simulation finishes. From Table 3, when Approach-1 is used, it is necessary to have a train on every double-track point from the commencement of the muck evacuation process. Otherwise, the operation For example, when there is no incoming train at a double-track point, no outgoing train is allowed to pass the double track, resulting in a deadlock. Cases 4, 10, 13, and 16 in Table 3 are those where there is no deadlock. In these cases, the number of supply trains equals the number of double-track points plus two, which means there is a train stopped at every double-track point from the commencement of the muck evacuation process plus a train at the shaft and another train at the TBM.

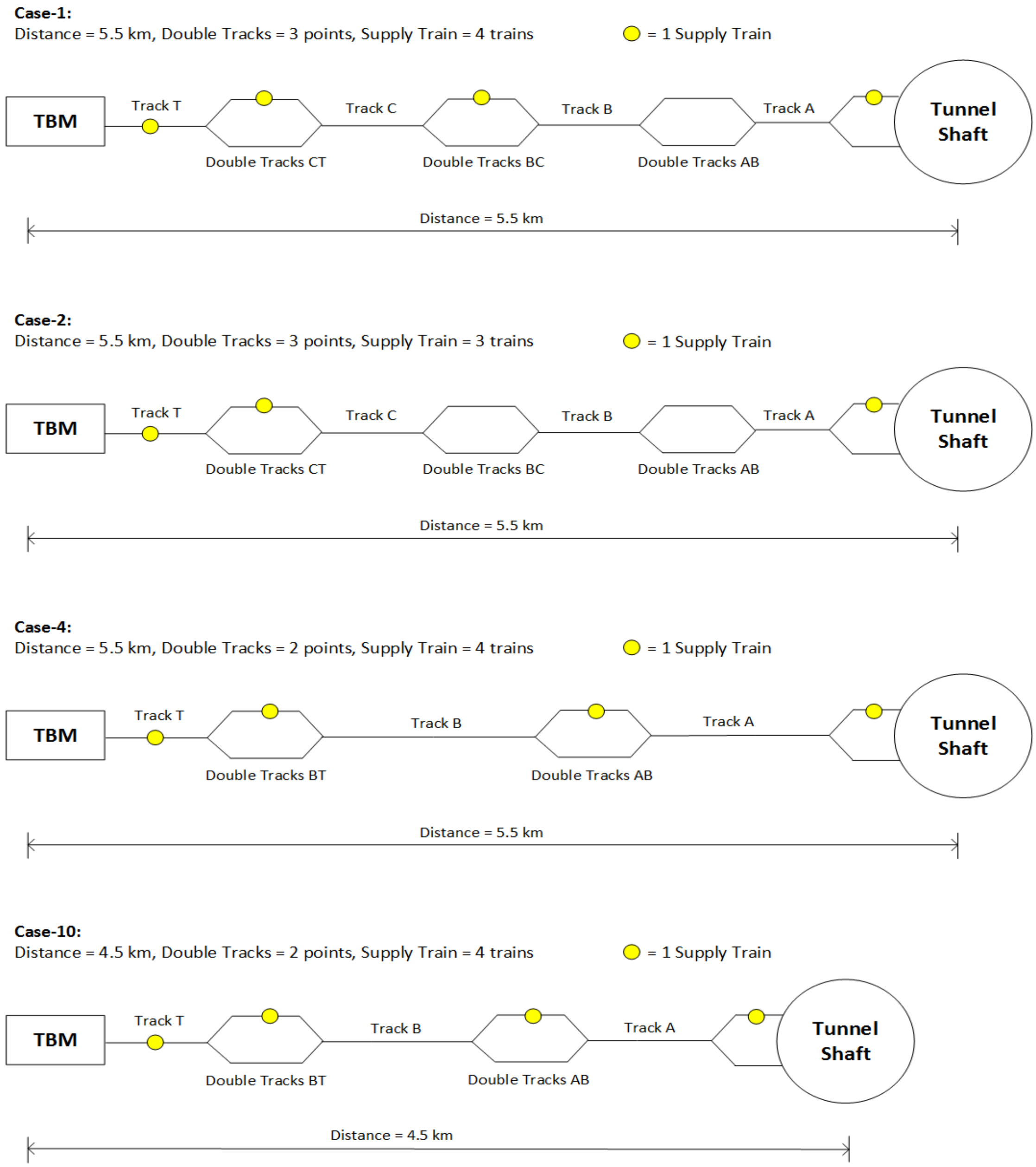

Fig. 8. Track layouts of cases 1, 2, 4 and 10 from Table 1

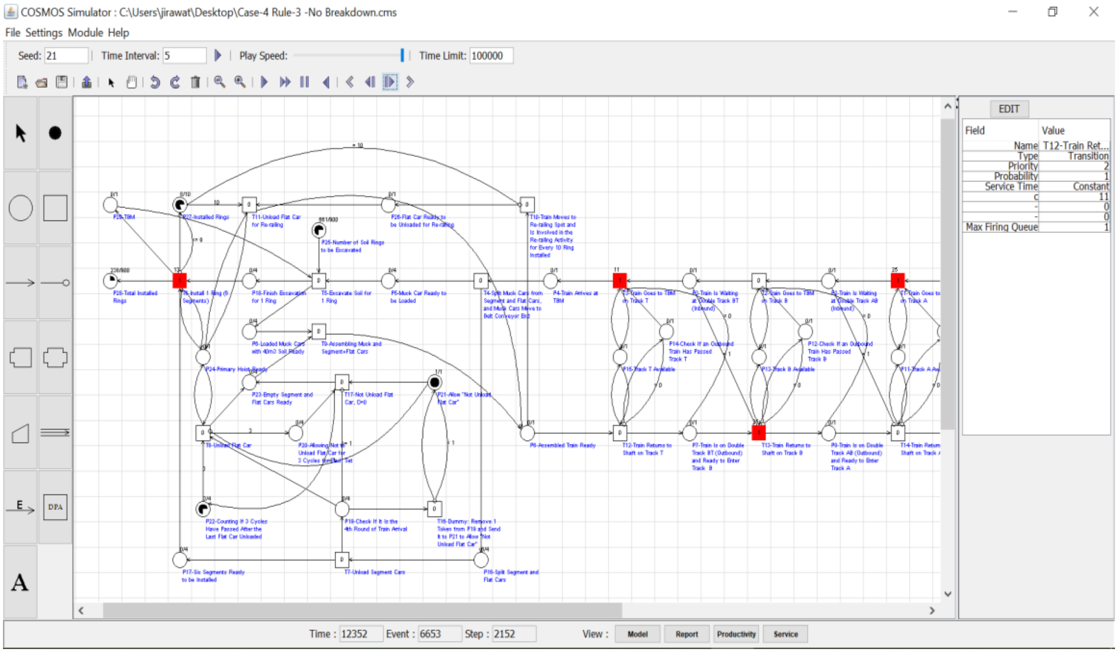

Fig. 9. COSMOS simulator's interface when running model for case 4 of Approach-1

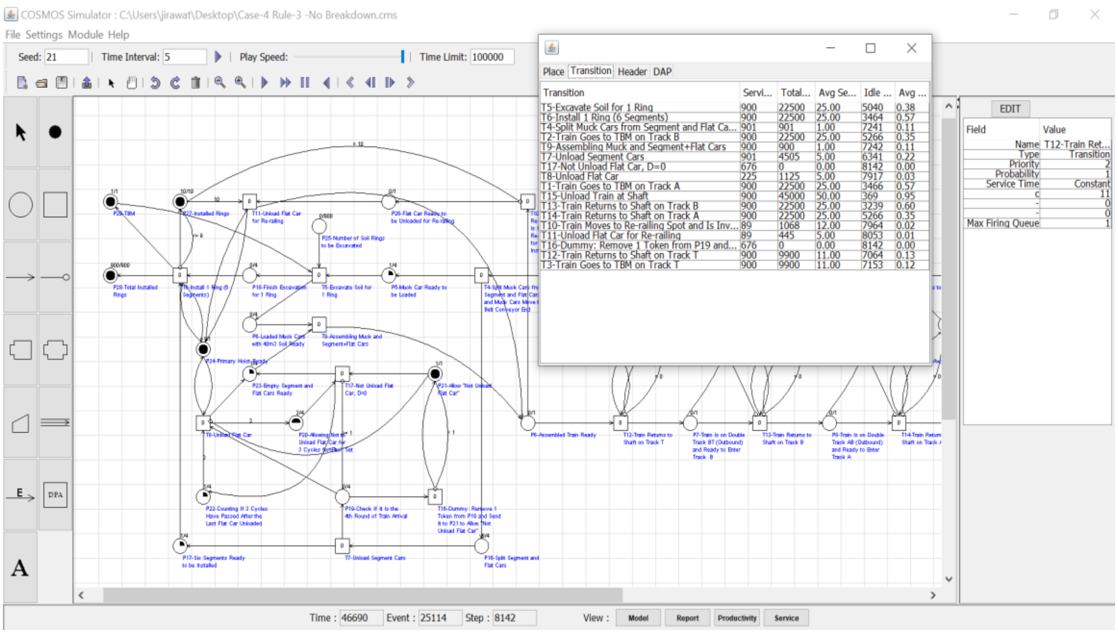

Fig. 10. COSMOS simulator's interface when simulation run finished for case 4 of Approach-1

Table 2 Average activity durations for the operation

Short names	Activities	Activity durations (minute)
T1	Train Goes to TBM on Track A[a] (2.3 km)	25
T2	Train Goes to TBM on Track B[a] (2.3 km)	25
T3	Train Goes to TBM on Track T[a] (0.9 km)	11
T4	Split Muck Cars from Segment and Flat Cars and Muck Cars Move to Belt Conveyor End	1
T5	Excavate Soil for 1Ring	25
T6	Install 1Ring (6 Segments)	25
T7	Unload Segment Cars	5
T8	Unload Flat Car	5
T9	Assembling Muck and Segment+Flat Cars	1
T10	Train Moves to Re-railing Spot and Is Involved in the Re-railing Activity for Every 10 Ring Installed	12
T11	Unload Flat Car for Re-railing	5
T12	Train Returns to Shaft on Track T[a] (0.9 km)	11
T13	Train Returns to Shaft on Track B[a] (2.3 km)	25
T14	Train Returns to Shaft on Track A[a] (2.3 km)	25
T15	Unload Train at Shaft	50

a. For case 4 from Table 1 only.

Since the drivers of both outgoing and incoming trains can decide by merely using visual inspection to prohibit the collision of trains inside the tunnel, Approach-1 can be implemented with ease. The driver of an outgoing train can simply look at the approaching double-track point to see whether there is an incoming train parked at the track point. If so, the outgoing train can pass the double track. If not, the outgoing train must wait at the double-track point until the driver sees an incoming train passed the track point. Incoming trains use the same visual inspection rule. However, this approach is prone to an operation-deadlock problem if there is a lack of balance between the number of trains and the number of double-track points along the rail track.

More simulation results and analysis of the model implementing Approach-1 can be found in (Damrianant, 2018).

Table 3 Simulation results of Approach-1

Cases	Operation duration for 900 rings (minute)	Average number of rings installed in 24 hrs.[a]	Remarks
1	Deadlock [b]	N/A	Operation stops at t = 151 minutes
2	Deadlock	N/A	Operation stops at t = 101 minutes
3	Deadlock	N/A	Operation stops at t = 51 minutes
4	46,690	27.8	
5	Deadlock	N/A	Operation stops at t = 101 minutes
6	Deadlock	N/A	Operation stops at t = 51 minutes
7	Deadlock	N/A	Operation stops at t = 151 minutes
8	Deadlock	N/A	Operation stops at t = 101 minutes
9	Deadlock	N/A	Operation stops at t = 51 minutes
10	46,680	27.8	
11	Deadlock	N/A	Operation stops at t = 101 minutes
12	Deadlock	N/A	Operation stops at t = 51 minutes
13	46,670	27.8	
14	Deadlock	N/A	Operation stops at t = 101 minutes
15	Deadlock	N/A	Operation stops at t = 51 minutes
16	46,660	27.8	
17	Deadlock	N/A	Operation stops at t = 101 minutes
18	Deadlock	N/A	Operation stops at t = 51 minutes

a. The operation was performed around the clock.

b. Deadlock arisen from the absence of an incoming train at a double track, no outgoing train was therefore allowed to pass the double-track point.

Considering Table 4, Approach-2 gives more flexibility in managing a combination of the number of trains and the number of double-track points along the railway track, since no deadlock of the operation occurs for any of the 18 cases under study. Even though some combinations of the number of trains and the number of double-track points do not give the maximum productivity rate of 27.8 rings per day, no deadlock arises. Nevertheless, Approach-2 is more challenging to implement. Simply using visual inspection is not enough, but some devices or systems are also needed to prevent the collision of the trains within the tunnel.

Table 4 Simulation results of Approach-2

Cases	Operation duration for 900 rings (minute)	Average number of rings installed in 24 hrs.[a]	Remarks
1	76,204	17.0	
2	108,565	11.9	
3	139,219	9.3	
4	46,690	27.8	
5	90,603	14.3	
6	135,619	9.6	
7	51,346	25.2	b
8	70,845	18.3	c
9	121,219	10.7	
10	46,680	27.8	
11	81,613	15.9	
12	117,619	11.0	
13	46,670	27.8	
14	54,592	23.7	
15	99,622	13.0	
16	46,660	27.8	
17	46,660	27.8	
18	81,632	15.9	

a. The operation was performed around the clock.

b. At some points in time, an outgoing train had to wait on a double-track point for an incoming train to pass the track point since there was an incoming train running on the adjacent track and approaching the double-track point where the outgoing train was waiting.

c. There was a time when an outgoing train waited on a double track for an incoming train to pass that track point since there was an incoming train running on the adjacent track and approaching the double-track point where the outgoing train was waiting.

It should be noted that the productivity of this operation is measured in terms of the number of tunnel lining rings installed per day. One day equals 24 hours of construction. The maximum productivity predicted by the simulation is 27.8 rings per day with no breakdown of any equipment is included. This figure, therefore, represents the case where the operation runs smoothly. This predicted maximum productivity rate agrees with the average maximum productivity per day statistically recorded from previous projects by the tunnel-boring firm.

4. Conclusion

Two different approaches to track management for underground tunnel construction were studied. A 9.4 km long drainage-tunnel construction in Bangkok, with an inside diameter of 5 m, was used as a case. Petri Net- based models and COSMOS simulations were constructed and performed as the research methodology. The results indicate that the first approach can be more naturally implemented. However, this approach is prone to an operation-deadlock problem if there is a lack of balance between the number of trains and the number of double-track points along the rail track. The second approach was found to be more complicated to operate but had no deadlock issue. The second approach, therefore, yields flexibility in managing the track, as it allows more combinations of the number of supply trains and the number of double-track points. This information can be used as a guideline for choosing an appropriate track management approach for other applicable under-ground-tunnel construction projects.

5. References

Chen, M., Hariharaputran, S., Hofestädt, R., Kormeier, B. and Spangardt, S., 2011, Petri net models for the semi-automatic construction of large scale biological networks, Nat. Comput. 10: 1077–1097.

Damrianant, J., 2003, COSMOS: a discrete-event modelling methodology for construction processes, Int. J. Internet Enterp. Manag. 1: 128–152.

Damrianant, J., 2018, Optimization of Supply Trains in Tunnel Boring Operation Using Tunnel Boring Machines, 6th Int. Conf. Adv. Civ. Struct. Mech. Eng., p. 8-12.

Lv, Y.Q., Lee, C.K.M., Wu, Z. and Chan, H.K., 2013, Priority-based distributed manufacturing process modeling via hierarchical Timed Color Petri Net, IEEE Trans. Industr. Inform. 9: 1836-1846.

Rinke, N., Gösseln, I.V., Kochkine, V., Schweitzer, J., Berkhahn, V., Berner, F., Kutterer, H., Neumann, I. and Schwieger, V., 2017, Simulating quality assurance and efficiency analysis between construction management and engineering geodesy, Autom. Constr. 76: 24-35.

Roux, O., Duvivier, D., Quesnel, G. and Ramat, E., 2013, Optimization of preventive maintenance through a combined maintenance-production simulation model, Int. J. Prod. Econ. 143: 3-12.

Singh, K., Raj, N., Sahu, S.K., Behera, R.K., Sarkar, S. and Maiti, J., 2017, Modelling safety of gantry crane operations using Petri Nets, Int. J. Inj. Contr. Saf. Promot. 24: 32-43.

Si, Y.W., Chan, V.I., Dumas, M. and Zhang, D., 2018, A Petri Nets based Generic Genetic Algorithm framework for resource optimization in business processes, Simul. Model. Pract. Theory. 86: 72-101.

TERRATEC 2016, TERRATEC tunnel boring machine - EPB series, Available Source: https://www.youtube.com/watch?v=1XVkmbeB958, January 21, 2020.

Wakefield, R.R. and Sears, G.A., 1997, Petri Nets for simulation and modelling of construction systems, J. Constr. Eng. Manag. 123: 105-112.

Zhang, D.Z. and Anosike, A.I., 2012, Modelling and simulation of dynamically integrated manufacturing systems, J. Intell. Manuf. 23: 2367–2382.