International Journal of Railway Research, (2014), Vol.1, No2, pp 23-30 ISSN: 236153768187

Iran University of Science and Technology

International Journal of

Railway Research

Train Scheduling Problem - Phase I: A General Simulation Modeling Framework

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A B S T R A C T

One of the important problems in management of railway systems is train scheduling problem. This is the problem of determining a timetable for a set of trains that do not violate infrastructure capacities and satisfies some operational constraints. In this study, a feasible timetable generator framework for stochastic simulation modeling is developed. The objective is to obtain a feasible train timetable for all trains in the system, which includes train arrival and departure times at all visited stations and calculated average train travel time. The developed framework includes stochastic events, and can easily cope with the disturbances that occur in the railway systems, so it can be used not only for scheduling but also for rescheduling problems.The contribution here is the developed framework.

Keywords: train, railway, scheduling, timetabling, simulation

1. Introduction

Train scheduling (timetabling) problem is the problem of determining a timetable for a set of trains that do not violate track capacities and satisfies some operational constraints. A general train scheduling problem in the literature considers a single track linking two major stations with a number of intermediate stations in between [1]. The problem can be more sophisticated by adding some real life behaviour of rail systems or relaxing some assumptions made related with the railway system under consideration. In this study, after literature review on the problem, a timetable generator simulation model [2 and 3] is explained for obtaining a feasible train timetable in a railway system. The model includes train arrival and departure times for all stations visited by each train and calculated average train travel time.

Studies on the problem aim at achieving a train timetable with arrival and departure times of all trains at the visited stations in the system. These studies generally begin with a planned infeasible initial (draft) timetable with many conflicts. After these conflicts were solved a feasible train timetable is composed, and the train operating authority runs the trains according to the feasible timetable.

Papers that developed mathematical models to solve the problem are [4, 5, 6, 7, and 8]. On the other hand [9, 10, 11 and 12] used heuristics and metaheuristics as solution approaches.

Two study series draw an attention. The first serial includes four articles [1, 13, 14 and 15]. [1 and 14] concentrated on train scheduling problem relevant to a single, one way track linking two major stations with a number of intermediate stations between them. A graph

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theoretic formulation was proposed for the problem using a directed multigraph in which nodes correspond to departures or arrivals at a certain station at a given time instant. The objective was to maximize sum of the profits of the scheduled trains. [15] extended the problem considered in [1] by taking into account additional real world constraints. On the other hand [13] proposed heuristic and exact algorithms for the periodic and non-periodic train timetabling problem on a corridor to maximize the sum of the profits of the scheduled trains. The heuristic and the exact algorithms were based on the solution of the relaxation of an integer linear programming formulation in which each variable corresponds to a full timetable for a train. This approach was in contrast with previous approaches proposed by [1, 14 and 15] so that these authors considered the same problem and used integer linear programming formulations in which each variable was associated with a departure and/or arrival of a train at a specific station in a specific time instant.

The second serial consists of [16 and 17]. [17] focused on single track and proposed a generalized resource constrained project scheduling formulation for train timetabling problem. The developed algorithm chronologically added precedence relation constraints between conflicting trains to eliminate conflicts, and the resulting sub-problems were solved by the longest path algorithm to determine the earliest start times for each train in different segments. [16] used an optimization method to solve train timetabling problem for a single tracked bidirectional line, similar to the one presented by [17] but more complex, and discussed the problem of sensitivity analysis. A three stage method was proposed to deal with the problem and a sequential combination of objective functions was used for solution.

Recently [18, 19 and 20] have spent efforts to optimize multi objective train scheduling problems. In only a few papers [21, 22 and 23] simulation models have been developed for the problem. [23] was the first study that developed a simulation model for train scheduling problem. The output of the simulation model comprised a pictorial representation of the pattern of train movements as well as detailed statistics for each train. The problem was to determine where a crossing or overtaking should be allowed to occur, and the objective was to minimize the sum of weighted costs of delaying trains at passing loops where the weights chosen reflect the importance of each type of train. To improve the system performance, train starting times were varied, and one train at a time heuristic iterative procedure was used for improvements. [22] presented a state space description for the problem of moving trains over a line, and an algebraic description of the relationships that must hold for feasibility and safety considerations was given. The line blockage problem at high traffic intensities was discussed under conditions that ensure the blockage not to occur. The objective of the study was to minimize the terminating times of the trains. [21] focused on the railway scheduling problem and developed a constraint based deterministic simulation model with the objective of reducing the lateness of trains. Selecting alternative paths in stations was an optimization task to reduce lateness and to find a conflict free solution. The results of the proposed sequentially train scheduling heuristic was compared with those of a genetic algorithm.

Two books [24 and 25] give comprehensive knowledge on the problem. [24] described the methods of railway timetabling, operations analysis and modelling, simulation and traffic management in order to stimulate their broader application in practice. [25] provided basic knowledge in the science of railway operation in a close connection to signalling principles and traffic control technologies.

2. Simulation modeling

2.1 A Train Scheduling Problem

The infrastructure in the problem has a line structure inspired by a real railway line, and has a planned initial timetable with arrival and departure times of trains only at two end stations. The railway line is a single track corridor, and there are 10 real stations on the single track corridor that are labelled as S_i (i = 1, 2, …, 10) from the east to the west. The corridor has two terminuses, TS_1 and TS_{10}, which indicate the beginning and the finishing points. As it is seen in Table 1, the total track length from the TS_1 to the TS_{10} is 286270 meters. Since all the real stations have 200 meters platform, the whole length of the corridor is 288270 meters.

Table 1. Track lengths between the real stations

To / From	TS_1 (*East*)	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	TS_{10} (*West*)
TS_1	0	500	28070	60170	88400	125210	170060	197060	214460	243560	285770	286270
S_1	500	0	27570	59670	87900	124710	169560	196560	213960	243060	285270	285770
S_2	28070	27570	0	32100	60330	97140	141990	168990	186390	215490	257700	258200
S_3	60170	59670	32100	0	28230	65040	109890	136890	154290	183390	225600	226100
S_4	88400	87900	60330	28230	0	36810	81660	108660	126060	155160	197370	197870
S_5	125210	124710	97140	65040	36810	0	44850	71850	89250	118350	160560	161060
S_6	170060	169560	141990	109890	81660	44850	0	27000	44400	73500	115710	116210
S_7	197060	196560	168990	136890	108660	71850	27000	0	17400	46500	88710	89210
S_8	214460	213960	186390	154290	126060	89250	44400	17400	0	29100	71310	71810
S_9	243560	243060	215490	183390	155160	118350	73500	46500	29100	0	42210	42710
S_{10}	285770	285270	257700	225600	197370	160560	115710	88710	71310	42210	0	500
TS_{10}	286270	285770	258200	226100	197870	161060	116210	89210	71810	42710	500	0

The train arrival and departure times at two end stations are given in Table 2, where WB_i($i = 1, 2, \ldots, 10$) indicates a *westbound* train that begins its trip from the first real station on the *east* of the corridor and plans to finish at the first real station on the *west* of the corridor, EB_i ($i = 1, 2, \ldots, 10$) indicates an *eastbound* train which has an opposite direction to WB trains.

Table 2. Planned initial train timetable

Station	Train	Arrival Time	Departure Time	Station	Train	Arrival Time	Departure Time
	WB_1	00:00	00:10		EB_1	00:00	00:10
	WB_2	02:00	02:10		EB_2	02:00	02:10
	WB_3	04:00	04:10		EB_3	04:00	04:10
	WB_4	06:00	06:10		EB_4	06:00	06:10
S_1	WB_5	08:00	08:10	**S_{10}**	EB_5	08:00	08:10
	WB_6	10:00	10:10		EB_6	10:00	10:10
	WB_7	12:00	12:10		EB_7	12:00	12:10
	WB_8	14:00	14:10		EB_8	14:00	14:10
	WB_9	16:00	16:10		EB_9	16:00	16:10
	WB_{10}	18:00	18:10		EB_{10}	18:00	18:10

2.2 A Feasible Timetable Generator Simulation Model

The model is developed by using Arena discrete event simulation software in a modular manner. First, the railway corridor with links, intersections and the stations is modelled, and track failures and repairs are included. Then, train movement logic on the corridor is modelled. We use a rule for track allocation to candidate trains that are the trains waiting at neighbour stations of the track to use it. Fixed train speeds are relaxed, and additional unplanned delays at the stations are inserted. The number of trains in the system is increased and randomness is added to the planned initial train timetable. As a last step, animation of the system is developed.

Some assumptions are made during the modelling phase of the simulation model:

- The unit for length and time is meter and second, respectively.
- Time spent for reaching to a terminus from the park area is negligible.
- All the trains are the same type.
- Passengers are ignored at this level of the model.

- There is time headway (40 seconds) between two consecutive trains at a station, which have the same trip direction, in order to have a safe trip.
- More than one train that have the same direction can use the same track with distance headway (1000 metres) between them.
- Earliness and lateness time in the planned initial train timetable, due to some uncontrollable events that occur outside of the corridor, is uniformly distributed between -900 and +900 seconds.

The railway corridor is a union of intersections and links, and modelled via the *Networks Element* of the Arena. The links are the track parts on which train traverses during its trip from a station to another neighbour station. The links are modelled via the *Links Element* of the Arena. The intersections, connection points of the links, are modelled via the *Intersections Element* of the Arena. The stations are locations where a train can stop for boarding and alighting events, for parking or for waiting until a failure is accomplished. The real stations are interrelated with two intersections. The dummy stations are located on the tracks between the real stations to keep a train wait during the repairing of a failure, if the failure occurs while a train is traversing between the real stations. The stations are modelled via the *Stations Element* of the Arena. In the simulation model the links, the intersections and the track failures are controlled via variables. The *Variables Element* of the Arena is used for defining the variables.

Assumptions related to the railway corridor part of the simulation model are:

- The railway system is a single track line, a corridor.
- The traffic on tracks is bidirectional, two way.
- There are 10 real stations and 20 dummy stations on the corridor.
- Every middle real station has capacity of two trains, that is, there will be at most two trains at a real station at the same time.
- Every dummy station has capacity of one train, that is, there will be at most one train at a dummy station at a specific time.

Track failure is an event that prevents a train to occupy the impaired track for a trip. The train can use the track after it is repaired. In the simulation model, the track failures are controlled via variables. If a failure occurs in a track part, trains are prevented to use this part until it is repaired. If a track failure happens while a train is traversing on this track and if the next station is a dummy one, train goes to next dummy station and a check is made if the failure is on that train’s destination direction or not. If the failure is on its destination side, the train waits until failure is repaired, else the train goes on its trip.

Assumptions related to the train movement part of the simulation model are:

- Each train stops at real stations except terminuses.
- A train stops at a dummy station if there is a failure in a track placed in front of that train.
- Trains that have reverse directions can cross each other only at the real stations.
- Dwell times for each station are 600 seconds. That is each train will stop at least 600 seconds at the all stations for boarding and alighting events.
- To represent unplanned delays at a station, delay time is defined. It is assumed that delay time is exponentially distributed with a mean of 90 seconds. Delay time is added to the dwell times. Due to this unplanned delay, overtaking is possible.
- Track occupying decision is taken at the real stations based on the answers given the following questions; Are the links and

intersections suitable? Does a track failure exist? Does this decision cause a deadlock?

- First come first served (FCFS) dispatching rule is used to select one train among the candidate trains, which are the trains waiting at neighbour stations of the track that want to use the same track and has finished waiting for dwell time and additional unplanned delay time. Namely the candidate trains are the trains that deserved to begin checking the conditions. If the all conditions to move are suitable for a candidate train, which arrived first to one of the neighbour station of the track it will begin to trip, else the same check is made for another train arrived second. Checking goes on until a suitable train is found.

The strategies proposed to prevent the deadlock problem in railway systems are reviewed in [26]. The author concluded that the proposed models are based on the game board philosophy and are not suitable to be used in control logic of real simulation systems, and proposed a rule-based deadlock avoidance method for simulation systems which follows the idea that a specified number of track sections ahead of a train must be reserved before this train is allowed to enter a track section. The number of track sections to be reserved depends on a set of logical rules.

In our model long track sections are controlled in order to prevent a conflict which occurs if the long track section is used at the same time by the two trains in opposite directions. On the other hand, in order to avoid a deadlock that prevents the movement of the trains, we developed the *blockage preventive algorithm* [25 and 26] that does not control the track sections but controls the real stations. The algorithm follows the idea that the whole real stations in the direction of the train are checked before permitting the train to departure from its current station. The algorithm first checks the next station in front of the train while the train is in a station. For this train, if there is an empty capacity in the next station, the algorithm checks whether it is the last station or not. If the next station is the last station, the checking finishes and the train goes on its trip, otherwise the checking goes on for the station behind the next station and checking lasts until the last station is checked. The empty capacities of the checked stations and also the directions of the trains that occupy the checked stations are important. The algorithm checks the whole real stations in front of the train, it never permits a deadlock and guaranties to obtain a feasible train schedule. The aim is to prevent any train departure that will cause a deadlock in the future.

The simulation model is verified by developing the model in a modular manner, using interactive debuggers, substituting constants for random variables, manually checking the results and animating the system. The animation part of the simulation model was built by using the *Animate*tool of the Arena, to see if model is working as intended, and to understand the system clearer.

3. Research results

In this section a feasible train timetable obtained by the simulation model is given. The train-station diagram of the feasible solution of which the calculated average train timetable is 24218 seconds is given in Fig. 1.

In order to see what happens in the system after a failure has occurred, Fig. 2 should be examined. In this figure, while the simulation model is running through 39600-79200 seconds a part of the system between the stations dS_{31} and the dS_{81} is displayed. As can be seen in the dotted line circle denoted by 1, a failure occurred after the EB_8 train begins its trip from the S_5 to the S_4. Therefore, the EB_8 waits at the dS_{43} during the repair, and then the EB_8 and the EB_9 trains traverse on the track part between the S_5 - S_4.

While the simulation model is running through 39600-70200 seconds, a part of the system between dS_{43} and the dS_{71} is displayed in Fig. 3, which is the dotted line rectangle denoted by 2 in Fig. 2. In this figure, if we look at the dotted line rectangle, there is a track failure between the S_6 and S_7. After the track is repaired the trains can travel. But at that time there are more than one candidate trains waiting for using the repaired track part.

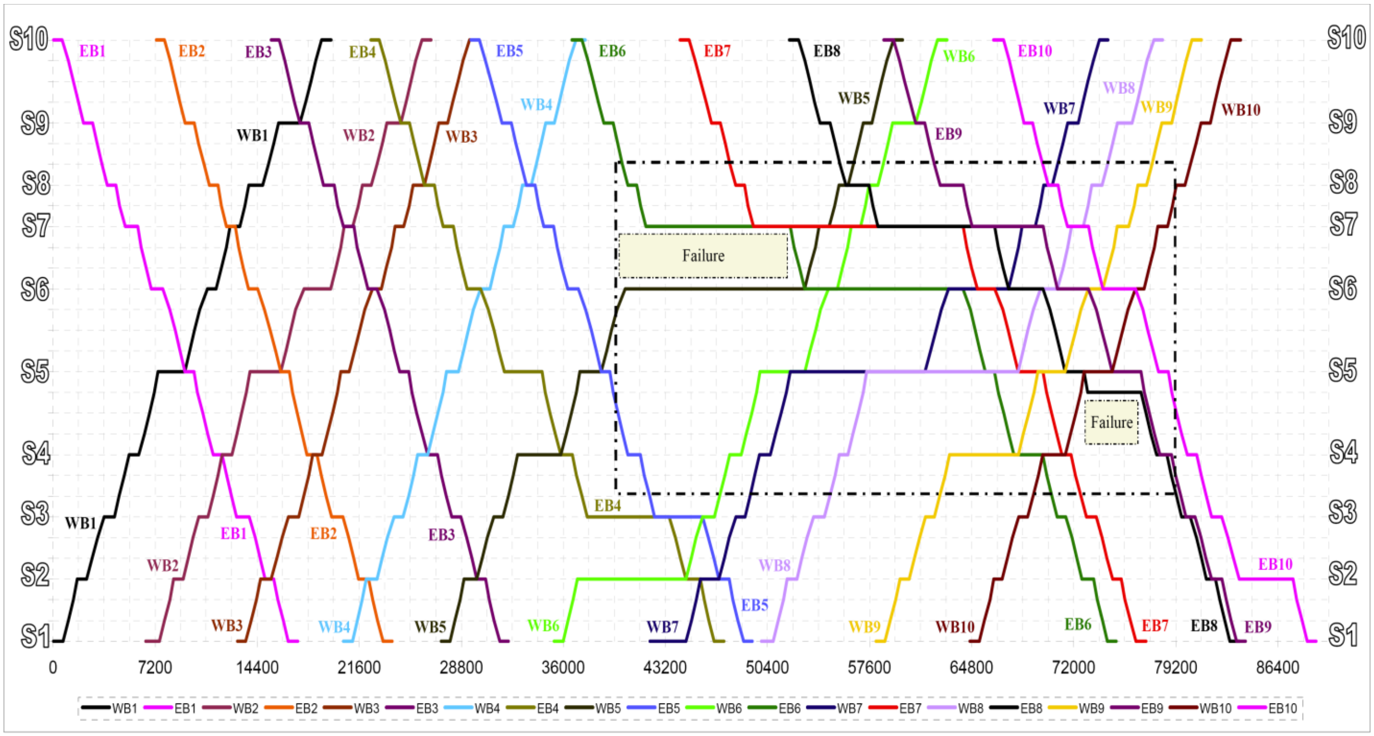

Figure 1. Feasible train-station diagram

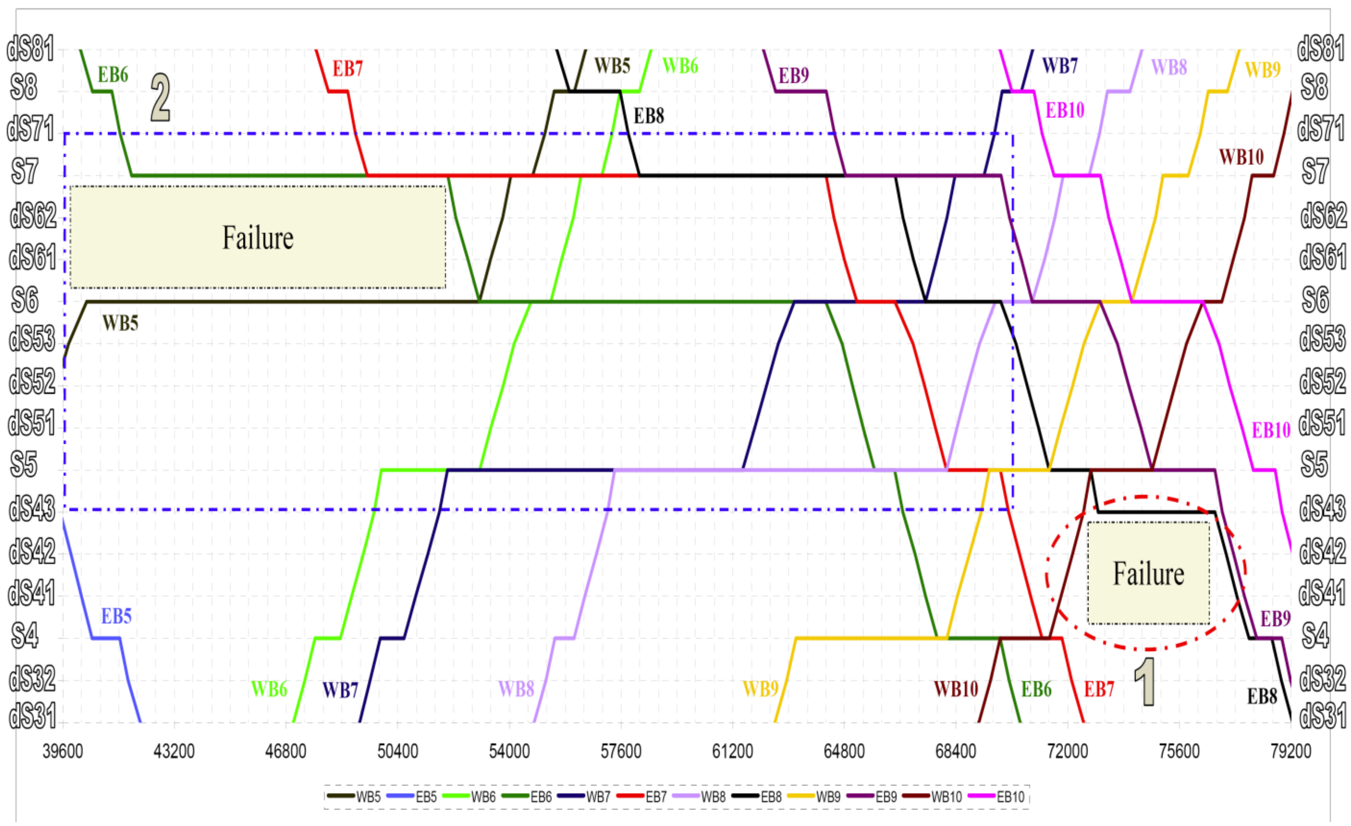

Figure 2. Feasible train-station diagram for the dS31-dS81 part from 39600 to 79200 seconds

To make it clearer we verbally explained the important events on the track part between the S_5-S_7, while the simulation model is running through 39600-70200 seconds, depicted in Fig. 3.

At 39600 seconds, all the three stations are empty, the WB_5 is travelling between the S_5-S_6, and there is a failure event between the S_6-S_7. After that, the WB_5 reaches S_6, the failure is still going on. Next, the EB_6

reached to the S_7, and then the other part of the S_7 is occupied by the EB_7, the trains are waiting because the failure is still going on.

four trains that have entered this part after the repair at this part.

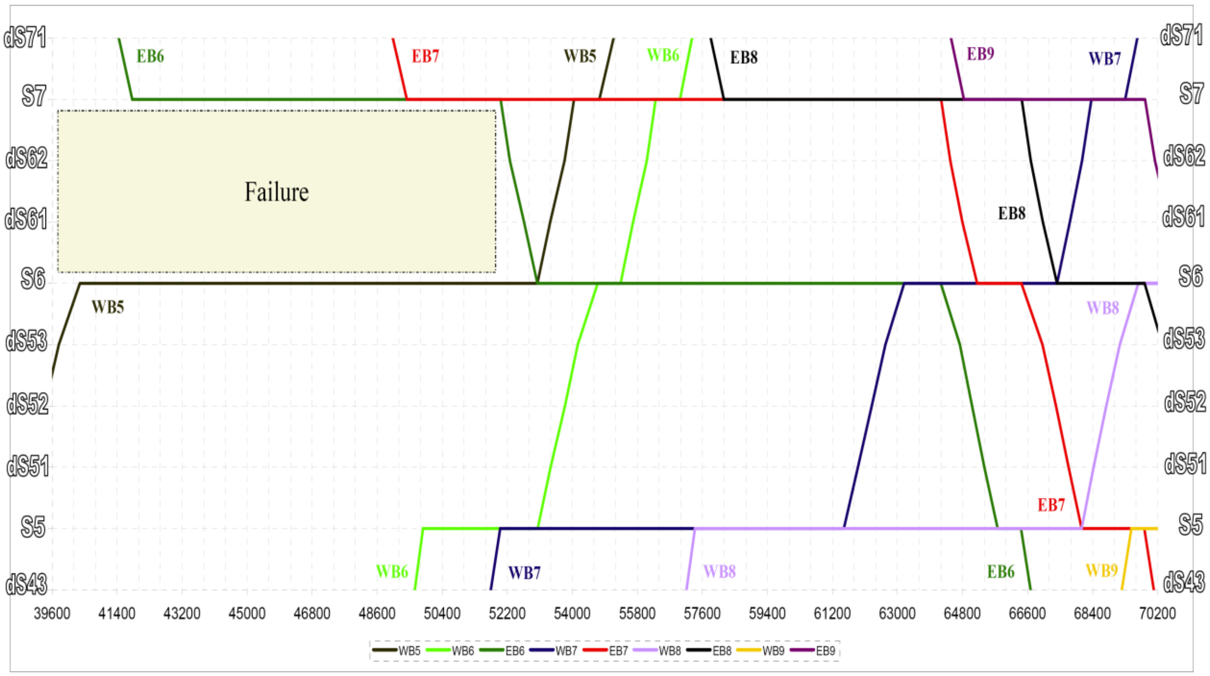

Figure 3. Feasible train-station diagram for the dS43-dS71 part from 39600 to 70200 seconds

Later, the WB_6 occupies the S_5, and then the other part of the S_5 is occupied by the WB_7. Although there is an empty capacity at the S_6, both the WB_6 and the WB_7 stop at the S_5, since a movement from the S_5 to the S_6 will cause a blockage. The failure is still going on, and the *five* trains are waiting for the track repair. After that, it is seen that the failure track has been repaired and has opened for the candidate trains. Although the first train in the queue is the WB_5, its move will cause a blockage. Thus, the EB_6 moves and uses the repaired track part. Next the WB_5 left and now there are four trains at this part (the track part between the S_5-S_7) of the system. Then, the WB_6 left, now there are three trains. After that, a new train, the WB_8, entered from S_5, now there are four trains. Next, a new train, the EB_8, entered from S_7, now there are five trains. Afterward, a new train, the EB_9, entered from S_7, now there are six trains. Then, the EB_6 left from S_5, now there are five trains. Next, the WB_7 left from S_7, now there are four trains. After that, a new train, the WB_9, entered from S_5, now there are five trains. Then, the EB_7 that is the last one entered this track part before its repair left from S_5, now there are four trains. Lastly, the simulation time is 70200 seconds and there are now

4. Conclusion

In this study, after giving a literature on the problem, a feasible timetable generator simulation model for the train scheduling (timetabling) problem is explained. The simulation model was developed to cope with the disturbances, therefore stochastic events were allowed in the simulation model. To cope with disturbances is also the interest of rescheduling (dispatching). Therefore, the simulation framework can also be used for the train rescheduling (dispatching) problem if it can be feed by the real time data. By using the presented approaches, the railway transportation systems can be modelled with only problem/infrastructure specific modifications and feasible solutions can be easily attained. Although simulation has been used in the literature, none of them included a comprehensive framework. The contribution here is the developed framework.

Acknowledgments

This study is supported by The Scientific and Technological Research Council of Turkey (TÜBİTAK).

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