Simulation model of a Single Track Railway Line

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Abstract – The analysis of the railway traffic with all complex processes involved can be effectively performed by computer simulation. Simulation modeling is an efficient tool for analyzing railway systems on an operational, tactical and strategic level. We present a discrete model for simulation of railway traffic on a single track railway line. Model uses hierarchy to connect levels and subsystems. State machines and flow charts are used to model how system reacts to events such as train route conflicts. Model was tested on a single track line for different train traffic scenarios.

I. Introduction

Railway traffic has an important role in mass transport of passengers and goods. Modern railways are in the process of restructuring to be able to compete on the transport market. Railway operators and infrastructure managers are interested in improving the efficiency and utilization of the railway system. This is especially important in the process of timetable design and planning. These processes must be fast and reliable, so there is an increase in computers usage, and specialized software for railway analysis and planning. Software for railway simulation are applied in all levels for operational, tactical and strategic planning.

Important part of planning or reconstruction of rail lines, and for traffic management is an estimation and analysis of the tracks or stations and nodes capacity and utilization [1, 2]. This task is dependent on the complexity and heterogeneity of rail transport and determines how to approach the problem and select the modelling tools. Complexity is correlated with the number of train categories, their speed profiles, and the infrastructure characteristics including number and location of the stations, number of tracks, and with the parameters of the timetables (trains overtaking and conflicting).

The train timetable is a precisely developed plan of train traffic that does not include train delays [3]. Unfortunately, disruptions of train traffic are very common in Serbian Railways. These disruptions can cause delays of trains and affect other trains causing secondary delays. It is not easy to predict disruption processes in a planning process because of theirs stochasticity. For the analysis of the train movements and interactions for a planned timetable it is common to use a simulation modelling approach by applying simulation software that are developed specifically for this purpose [4, 5, 6]. Commercial software packages like *OpenTrack* and *RailSys* [7, 8] use data on trains, infrastructure and timetable information to analyze the train movement and capacity consumption and utilization of the system. It is also possible to define scenarios and investigate impact of the incidents to the train operations and stability of the timetable. These incidents include train failures, infrastructure (signaling and safety) equipment malfunction, humane personnel mistakes and weather and other outside causes (by other transport modes etc.).

The aim of this paper is to present a simulation model developed in *Matlab* [9] that has ability to model a problem: efficient estimation of the single track train operations system parameters. The most important parameters are ones that describe capacity utilization by the number of trains that can operate on the line, utilization of the critical points of the infrastructure (station tracks and switch blocks) and train delays for the defined timetable. Proposed model is able to simulate all the conditions and restrictions imposed by operating rules in Serbian Railways. Further, it implements stochastic disturbances by importing train primary delays (generated by theoretical distribution) into the simulation model. Train primary delays affect the stability of timetable because of their impact to other trains that share same connections or cross their paths generating train conflicts. Because of that, this simulation model has a module for resolving train conflicts. The module based on flow charts theory is located as a subsystem within a simulation model.

II. Problem Description

The simulation model is developed for single track section of a railway line, with 9 stations with defined station tracks and train routes. As an input data for timetable we have defined train categories on the line as well as their speed profiles, acceleration times and times for passenger operations in the stations. Trains are operating in both directions, but some of the local trains are additionally using first two stations.

Following of trains or trains spacing is organized by station section block, that is, there is only one train on a section between two stations [10]. Dwell time for passenger trains is one minute in each station, and stopping time for freight trains is dependent on the current traffic situation. Freight trains have smaller priority then passenger trains, so the dispatching of the freight train is possible only if it does not influence the passenger trains operations. Stations for passing and overtaking are not determined in advance but rather determined during the simulation. Also, it is not possible that freight train can overtake a passenger trains. Freight trains will be operating on the section according to the location and movement of passenger trains, so the dispatching of the freight train will be possible only if the occupation of the next section will not affect the movement of other passenger trains. These rules regulate train traffic with the higher priority for trains of higher category, i.e. Passenger trains.

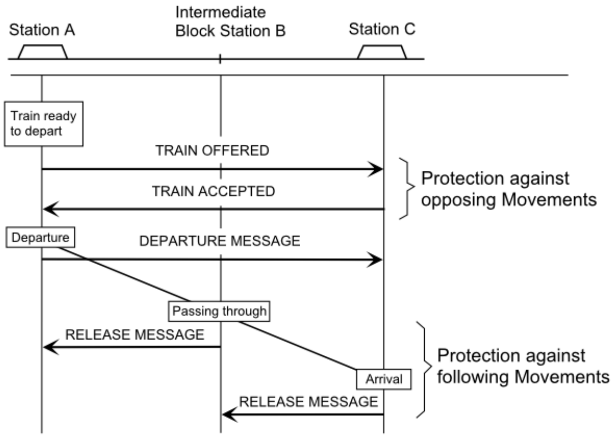

Figure 1. Procedure for train movements on single track line (*source: http://www.joernpachl.de/)*

Simulation model has properties that correspond to typical general decision making logic of a train dispatcher for a single track line. This includes route conflicts situations for same or different priorities (categories) trains. Dispatcher logic is included in the decisions regarding overtaking of trains, passing of trains different categories and spacing of trains. Specific state in the system is a moment when the dispatcher asks for a permission to dispatch train from the station, because received permission includes the information that there is no trains of any priority that will cause a conflict (Fig.1).

III. THE MODEL OF SINGLE TRACK RAILWAY LINE

The simulation model was designed in *Matlab* with tool *Simulink*. *Simulink* tool includes the *SimEvents* tool for simulation of discreet event systems, and tool for modeling of state flow, *Stateflow Chart.* Simulation model is based on discreet events and has a combination of blocks for discreet modeling, blocks for modelling of state flow charts and basic *Simulink* blocks.

Basic concept of the model is a queuing theory, where queues and servers are connected to create subsystems of the train traffic system, with gates to allow or deny a change of state. Open gate is allowing an entity to entry to a next object. Entities represent a train in model, and gates are signals or other conditions that enables the train movement.

Movement of entities thru the model is by subsystems that contain blocks (queues and servers) and decisions are created in the Stateflow Charts subsystem based on the information received from the objects that register the movement of the entities and previous decisions made. Model is organized in two sections (Fig. 2):

- Subsystems that represent station and track sections, and line sections that are connected according to the rail line section plan,
- Diagrams of state flows with implemented decision logic for train traffic management.

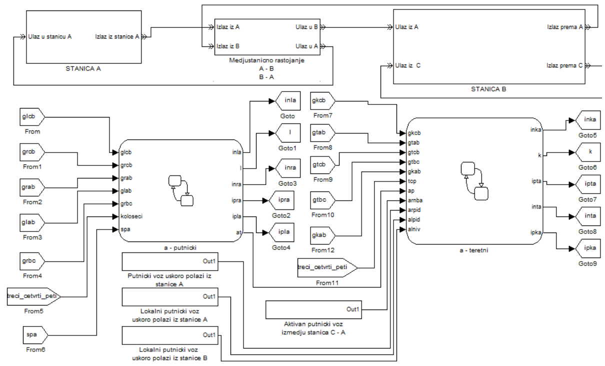

Figure 2. Part of the simulation model

In stations that are used to form a train there is a generation of entities by predetermined schedule of departures (deterministic schedule). After leaving the generating block, entities are assigned with attributes. Attributes are related to parameters regarding train times by sections, train times in stations, and attributes for route choices thru the model (directions of train movements). In starting stations we did not defined the number of track, because there is enough of capacity in those stations. Number of tracks is defined for all of the station along the route on the rail line.

A. *Models for intermediate stations*

Intermediate stations must be defined so that we can simulate the regulation of train movements. Additionally, we need to define available track capacity and specific use for tracks in each station, for all train categories, for both directions of train movement. We have 7 intermediate stations in the model that are similarly modeled but different by the number of tracks (Fig.3).

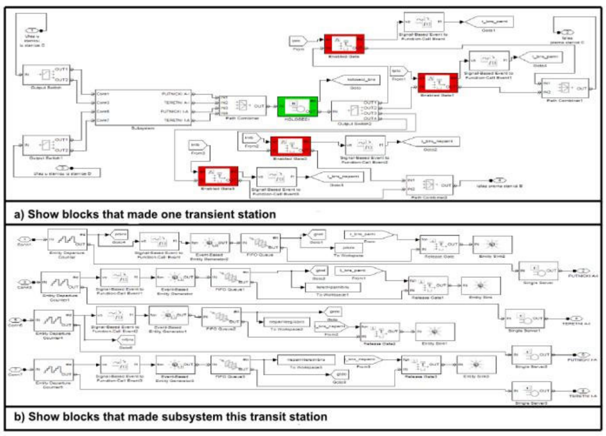

Figure 3. Blocks for representing the intermediate station in the model

Time of train dwelling in stations are determined only for the operations with passengers (leaving and entering the train) but will dependent on the traffic situation including the passing and overtaking of trains and waiting for the clear section (signal to allow the departure). To enable this and record the dwelling or waiting of trains on station track we have used queues on all tracks that have exit signals. Station is modeled to so that all the conditions and rules in real systems are applied to the model. After arriving in the station, entities (trains) are directed to the *OutputSwitch* according to the direction of movement.

From both directions, two categories (passenger and freight) of trains are directed to one of four gates in to the subsystem of the station (Fig. 3a). In the subsystem (Fig. 3b), each entity is directed to the counter (*block Entity Counter)*. Counters have attributes with variables that increase with entry of new entity. Counter information is sent to the block of the signal (Signal Based Event Based to Function Call Generator). Exit port of this block is connected to the block of the entity generator set to generate a new entity by receiving a signal. Entity that has passed the counter generates a new entity that is its copy. A copy is stored in one of four FIFO queues, which represent fictive station tracks. FIFO block, through the port *n*, forwards the information to the *State flow chart* on the number of entities in this queue, and thus provides the knowledge about arriving train's category and direction. The original entity, which has passed through the counter, progresses towards a single channel server with service level from zero minutes to update the attribute value in the counter, and then comes out of this subsystem to be stored on multi-channel server. Multi-channel server specifies a real number of tracks in the station and the arrival of the original entity corresponds to entrance of its copy to the queue. This multi-channel server specifies the service time for entities (i.e. the dwell time of each train in the station). Therefore, all original entities that represent trains are sent to the multi-channel server and their copies are stored inside separate FIFO blocks, according to the train category and direction of movement. The state flow charts gather the total station occupancy by all trains and store information on the category of those trains and the direction of movement.

Multi-channel server is connected with the block for routing entities to multiple outputs. Block for routing entities has four output ports, as two categories of trains can be dispatched to both directions from intermediate stations. Each output port is connected to its block gate (*Gate Enabled*) that enables or disables the departure from the station. If the gate is closed, the output port connected to that gate is blocked and entity cannot enter into the block for routing (*Output Switch*), so entity will remain in the multi-channel server (i.e. on track). According to this feature of block *Output Switch*, to disallow the processing of the entity if its output port is blocked, model can simulate the passing of trains, because one entity can be held in the multi-channel server while other entities are processed through the server. The state flow chart controls working of gates. In Fig. 3a, the first two gates (as viewed from above to the bottom) allow or forbid the departure of passenger and freight train to the right side of station, and the third and fourth allow or forbid the departure to the left side. Thus, it may happen that two gates allow the output to the following combinations: first and third, first and fourth, second and third, second and fourth. These special circumstances correspond to the simultaneous departure of two trains from station on the opposite sides.

After obtaining permission to leave the station, the original entity leaves the multi-channel server, executing the opening of the gate (*Gate Release*) in front of a fictitious queue of copy. After that the copy of original entity is terminated. If the gate *Enabled Gate* is closed for a particular type of entity it means that entity and its copy cannot leave the multi-channel server and the fictional FIFO queue. In this way rule is applied to dwell the entity as is not subject to general rules, such as FIFO or LIFO. Leaving the queue by the original entity depends on the rules implemented in the state flow charts, as they are responsible for the operation of gates *Enabled Gate* that allow or prohibit departure from the station.

This way of modeling intermediate station with embedded adequate rules to control the flow charts enables simulation of trains running in different directions to pass each other or trains heading in the same direction to overtake.

Regarding the sections between neighboring stations, every section between stations is presented using single-channel server. Data about occupancy is also sent to the state flow charts. Upon arrival of entity in single-channel server, its attribute attached during the entity creation could be used to evaluate running time on observed section. This attribute can vary, so trains with different velocities could be observed.

B. Train dispatching rules

Train dispatching is managed by state flow charts and they receive data from blocks in *SimEvents*. There are constructed certain states (*State*), which can be active and inactive. The states are interconnected corresponding to the conditions of transitions (Fig. 4). The states consist of actions that are executed when a given condition becomes active. Conditions are arranged in the term of exclusive *OR* relations, i.e. relation that is mutually exclusive of activity. An active state, means making a single decision, such as the prohibition of new train movement between stations, based on the fulfillment of a condition (occupied open line between these stations).

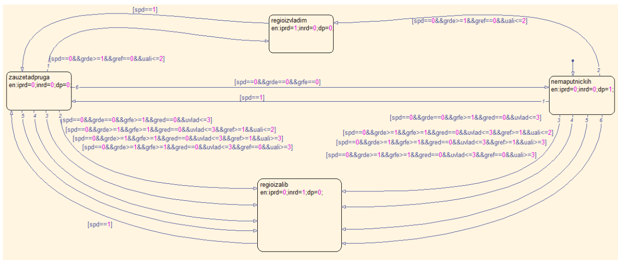

Figure 4. Stateflow chart of the model

Transition assessment from one state to another is performed according to the priorities, so that the execution of one transition means that the other does not execute. Also, it is necessary to define the state to be achieved when the first graph is activated.

State flow charts have the task to regulate the operation of the gates (*Gate Enabled*). Data about the entity position, data about track occupancy in the stations and open line occupancy are sent to the state flow charts. Based on the embedded rules, state flow charts enter into a certain State and define the output data from the charts and forward them to the gates (*Enabled Gate*). These gates should be understood as an output signals in stations or decisions of train dispatcher that permit or prohibit the train movement after he made sure in these decisions (assurance in the model performs state flow charts). Figuratively, this is shown in Figure 5. In the model, an open line between two stations is regulated with two state flow charts so that means that these two charts regulates as much gates as different categories of trains run on this section of the railroad. In addition, one chart is responsible only for the gates through which passing passenger trains and the other for the gates for freight trains. Hypothetical railroad comprise of 8 open line sections between stations, but in the model there are 16 of these charts.

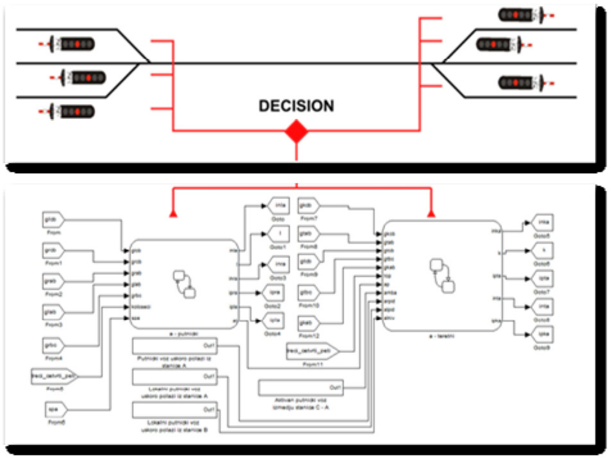

Figure 5. Principle of flow chart modeling

Regulation of entity movement in the model is defined by certain rules. These rules are different for passenger and freight trains, and differ between stations. The rules are set up so that passenger trains have priorities.

In general for this model, the departure of a passenger train from the station is possible, if all the following conditions are fulfilled:

1. The open line between stations should NOT be occupied by other vehicles.
2. There are *n-1* unoccupied tracks in the next station, where *n* is the total number of tracks in the station.
3. There are NO trains with the same rank and the same direction in the next station.
4. If the next station has to depart passenger train in the opposite direction, priority is given to the train which first has met the previous conditions. If both trains have met these conditions simultaneously, priority is given to the train with longer journey travelled.

General rules for the freight train departure from the station implemented in the model include following conditions:

1. Unoccupied distance between stations on which this train should be dispatched,
2. There are less than *n-1* tracks in next station, into which this train is departed, where *n* denotes the total number of tracks in this station,
3. There are no trains of the same rank and the same direction of movement at the departing station,
4. There is no passing passenger train at the departing station,
5. There is no passenger train with the same direction of movement, at the station where this train is located,
6. If there is a passing freight train at the sending train station, priority is given to the train that first meets all previous conditions. If these conditions are met for both trains, priority shall be given to the train that travelled longer journey.
7. If it is estimated that the dispatching of this freight train to the next station will not cause any passenger trains delaying.

The rule No. 7 is complex as it is necessary to combine several parameters to able to process it. Those parameters are collected by inspecting the position of trains on neighboring railway section. This problem is solved by setting up fictitious boundaries of this hypothetically railway section, in which the existence of passenger trains affects the decision of freight trains delaying. Fictitious boundaries are intended to include an area of several train stations and block sections between them. In the model, arrival of the entity that represents a passenger train at a place that represents the beginning of a fictitious boundaries, initiates a copy of that entity who is placed inside of storage block. When the original entity leaves the imaginary boundaries, its copy is terminated. On this way the reservation of the transport route section is completed for the passenger train, so it is unavailable for freight trains until the passenger train left the section. Information about the reservation of this segment is sent to the *Stateflow Chart*, which controls the movement of freight trains within this area. In this way, an absolute priority to the passenger trains is provided.

The set of rules, which can be seen in the Stateflow chart, provide solving the problem of giving permission to the train station, taking into account the train priorities and tracks capacities. It should be noted that during the process of experimenting these rules can be changed depending on the requirement settings.

IV. Model Verification

The duration of the simulation is set to 1440 minutes. We recorded the moments of arrivals, delaying and departures of entities from the subsystems that represent train stations, i.e. tracks in them. Based on these results, the model was verified graphically, by creating the train time diagram, for this hypothetical section of the railroad. The basic layer of train time diagram containing time scale on the horizontal axes and position of stations and length of open line tracks (in suitable drawing scale) is prepared in advance for this case study of single track railway line. Then, using the data obtained from the simulation model (results of the simulation), the diagram is filled with train routes. Events of entity transitions in the model correspond to the moments of appearance of entities in the observed points. These events are points (stations) of the train routes on the diagram. The train time diagram is drawn for the entire period of simulation performance and one part is shown in Figure 6. The *X*-axis represents time of 24 hours and is divided into hours and minutes, where lines of minutes are at 10 minute intervals. The ordinate represents the length of the railway line and intermediate stations are horizontal lines. Blue color shows the routes of freight trains, and black color the routes of passenger trains. In terms of distance, this hypothetical section is designed to suit the route of 70 kilometers.

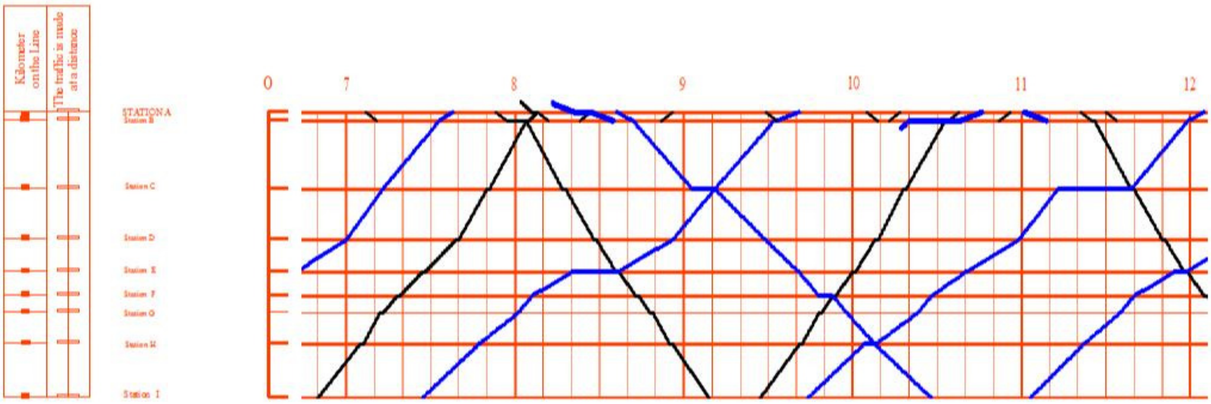

Figure 6. Results presented on a train diagram

V. ANALYSIS OF THE SPECIFIC TRAFFIC SCENARIOS

To better understand results obtained by simulation we have presented them as train time diagrams for two specific scenarios. First scenario is for train overtaking (Fig. 7). During train operations there is a need for overtaking of train when the train with higher speed gain on lower speed train. This is foreseen in the model for the following of two trains of different categories, and it is the case of passenger train overtaking freight train. Figure 7 shows the case of overtaking of slower train, where blue line is a route of the freight train that operates in the model between two stations, and black line shows route of the passenger train.

Train management is implemented by rules imposed by state flow chart. Diagram of the state flow chart that manages the movement of the entity (freight train on Fig.7) had an active state of closed gate until passenger train arrived at the station, and after arrival the state flow changed the transited to the status for allowing freight train further movement. The conditions for the passenger trains were enabling all gates to be opened.

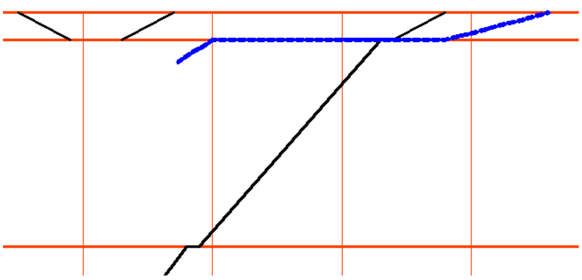

Figure 7. Overtaking of trains in the model

Another specific situation showed on Fig. 8 is for the passing of trains. Passing of trains is event of two train's movement in opposite directions for a single track line. In Fig. 8 freight train (blue line) after arrival at the station is waiting for passing of the passenger train (black line). After the arrival of passenger train to station, the section of the open line is released thus creating conditions for departure of the departure of the freight train.

Figures 7 and 8 shows that the rules and procedures applied in real systems by train dispatchers are successfully implemented in the simulation model, and that for these specific conditions of train traffic model is performing well. Graphical presentation of the results obtained from the simulation enables easier analysis of the modeled system and during the testing assists in verification of the simulation model. Also, graphical results enable the analyst to spot untypical situations and to test possible resolutions for the traffic problems.

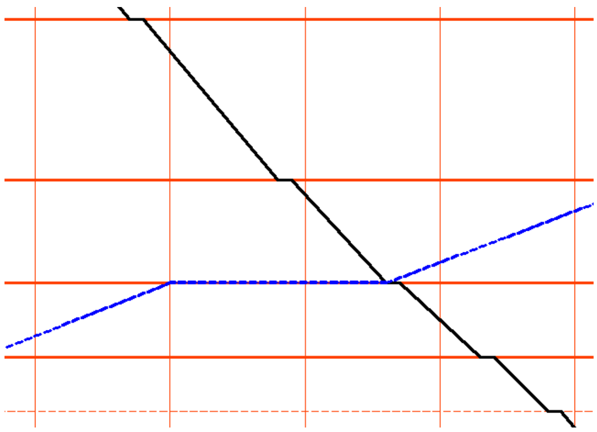

Figure 8. Passing of trains on the singe track line

Results collected in the database and graphical results showed that simulation model is performing according to the set of principles and rules imposed. Detail analysis of the results shows:

- Model has generated the trains as determined in input data with the exact time of departures for each train. Timetable was executed correctly.
- Passenger trains have dwell times in intermediate station as planned by timetable.
- Passenger train did not have delays caused by freight trains movement.
- Model performs adequately according to the rule imposed by the train dispatcher's logic.
- Principles of train spacing applied within a model are verified by graphical results (only one train on one block in one moment of time).

Other results obtained from the model are not presented in this paper as this would require a more detailed presentation on input data, modeling principles and results obtained from experimenting with simulation model. For example, this model was tested with a deterministic timetable, but in testing of the model it is necessary to include stochastic disruptions that cause primary train delays [6].

VI. Conclusion

Simulation of the discrete events by Matlab tools enables efficient approach in analyzing of complex systems like single track railway lines. During the development of the simulation model it is possible to include several tools for an integrated approach. Presented model was developed by combining blocks from SimEvents, Stateflow Charts and other basic blocks.

Model for simulation of single track railway line was developed for application in tactical and strategic planning in railways that have operating principles similar to Serbian Railway. Advantage of this model is its modular approach where subsystems can be managed and connected in the same level or form of the hierarchy. This supports building of the simulation models of different level of details, ranging from the micro models to macro models. Another important advantage is the Matlab environment that can be used not just to simulate, but also to include simulation model (as subsystem, or its results) into an optimization model. The disadvantages of the model are its complexity and necessary amount of knowledge and time to learn how to adjust and build the model. Further work on the simulation model will be directed to improve its ease of use and application in the real systems modeling. Also, research is planned for analysis of the data necessary to calibrate the model and for statistical analysis of the disruptions and causes that generates train delays. Another line of research will be directed in developing the Stateflow Chart model for the use in resolving train route conflicts in single track and double track lines and railway stations. Properties of Stateflow Chart such as management of timed events enables the new approach and new applications in modelling complex railway systems.

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References

[1] M. Čičak, S. Vesković, "*Organizacija železničkog saobraćaja II*", Beograd, Srbija, Saobraćajni fakultet, 2005.

[2] M. Čičak, "*Modeliranje u železničkom saobraćaju*", Beograd, Srbija, Saobraćajni fakultet, 2003.

[3] I.A. Hansen (ed.). "*Railway timetable & traffic: analysis, modelling, simulation".* Eurailpress, 2008.

[4] N. Bešinović, S. Vesković, M. Ivić, S. Milinković, Simulacioni model za utrvđivanje propusne moći pruge Novi Beograd - Batajnica primenom metode UIC 406, in: YU INFO 2011. (Informaciono društvo Srbije, Kopaonik, Srbija), 2011.

[5] N. Grubor, S. Milinković, S. Vesković, P. Márton, "Simulation analysis of the regional railways in South Banat region", *Railway Transport and Logistic*, vol 2013/3, 2013.

[6] S. Milinković, M. Marković, S. Vesković, M. Ivić, N. Pavlović, A fuzzy Petri net model to estimate train delays, *Simulation Modelling Practice and Theory*, 33, 144-157., 2013.

[7] Huerlimann, D. and Nash, A. "Open Track Simulation of railway network Version 1.3.", Institute for Transport Planning and Systems, Zurich, 2010.

[8] U. Fischer, S. Mirković, S. Milinković, A. Schöbel, "Possibilities for integrated timetables within the Serbian railway network", *Facta universitatis-series: Mechanical Engineering*, 10 (2012) 145-156., 2012.

[9] H. Klee, R. Allen. "*Simulation of dynamic systems with MATLAB and Simulink*". Boca Raton, FL: CRC press, 2007.

[10] J. Pachl, "*Railway operation and control".* EuRailPress. 2002.