Model for Control of Train Traffic on Junctions by Petri Net Simulation and Fuzzy Logic

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Abstract - **Railroad Junction is a place on the railway line where another line diverges. It is a complex system that is very difficult to describe and analyze by analytical or graphical methods. High Level Petri Nets - HLPN (timed, colored, stochastic and hierarchical) as a simulation tool can be used for graphical and mathematical modeling of various systems. HLPN model of junction comprises of interlocking and operating rules and input data for timetable, infrastructure and train characteristics. Model computes parameters of junction system and experiment by varying input data. HLPN have a good graphical presentation of model and can present results by animation or by tables and graphically by train time – distance graph. Trains primary delays are calculated by fuzzy logic system. Model is tested on a part of Belgrade railway node.**

Keywords – **Petri Nets, Railway Simulation, Fuzzy logic, Railway junction**

I. INTRODUCTION

Railroad Junction is a place on the railway line where another line diverges. It is a very complex system that is very difficult to describe with analytical models. Simulation model can compute parameters of junction in different operating conditions. Simulation tool must be able to make a model that will incorporate all interlocking and operating rules and data. Petri Nets are tool for graphical and mathematical modeling of various systems. High Level Petri Nets - HLPN are (timed, colored, stochastic and hierarchical) are tool that can model complex system and have a good graphical presentation of model.

Three different approaches are possible [1]: analytic methods, microsimulation methods and statistical analyses based on empirical data. Simulation models are detailed representation of a railway system and the only reasonable way to model in detail railway processes where different trains interact with each other and with the infrastructure. They require very detailed data about the infrastructure, the performance of the trains and, most importantly, about the timetable. If one of these data is unknown it is necessary to make assumptions and then results depend on the quality of input data.

Fuzzy logic is proved to be a good mathematical tool for modeling traffic processes that are distinguished by subjectivity, uncertainty, ambiguity and imprecision [2]. Many authors use advantage of predictive modeling systems with fuzzy logic. Fay [3] used fuzzy system as a dispatching support system for use in railway operation control systems. The model is defined as a fuzzy Petri net model that combines expert knowledge of fuzzy systems and graphical power of Petri Nets, making the model easy to design, test, improve and maintenance. Cheng and Yang [4] proposed fuzzy Petri Net model that will use professional knowledge of a dispatchers to create database rules to be applied for testing the system in case of disorder.

Fuzzy logic model for calculation of trains primary delays on junction use the experience and knowledge of railway personnel who directly participate in regulating the traffic in system.

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II. PETRI NETS AS A TOOL FOR MODELING OF A JUNCTION SYSTEM

Petri nets are a mathematical tool for modeling used for analysis and simulation of concurrent systems [5]. The theory of Petri nets is based on a mathematical theory of bipartite graphs. A bipartite graph (or bigraph) is a graph which nodes can be divided into two disjoint sets V_1 and V_2 such that every edge connects a node in V_1 to one in V_2; that is, there are no two identical nodes in the same set. Petri net is one of several mathematical descriptions of discrete distributed systems. The system is modeled as a bipartite directed graph with two sets of nodes: the set of places which represent state or system objects and the set of events or transitions that determine the dynamics of the system.

Petri Net model of junction

In Petri net model *places* represent sections, *transitions* represent conditions for train movement, and *tokens* represent trains. Hierarchy of the model enables defining insulated section as a subsystem or module. Insulated section can be block section, switch section and station track section. A module is defined for each distinctive section. Model is created by positioning and connecting modules according to the railway line section plan. Although this approach requires more time for initial programming, it allows using defined modules for modeling systems with similar processes. Module for generating trains imports timetable data from an external database for generating tokens (trains). Also, each token is filled with information about train it represent (train number, category, time of entering into the system, train route etc.). Defined tokens leave the module when the simulation clock and time of train departure match. Module of block section (Fig. 1.) represents a block section on an open line. The module contains *places, transitions,* storages for storing parameters and objects for connecting with other modules. Transitions in module enable or forbid entering and leaving the section based on the storage data. Storages contain information about state of the connected sections and signals and simulation clock. When the transition *trainin* enables firing, token are placed in *sectionbusy.* At the same moment, information about the occupancy of the section is sent to the previous two sections and to the signal. Token remains in place while conditions defined in the transition *trainout* are met:

- time needed for train to cross section - section occupancy time (train traveling time on section),
- next section is occupied,
- and signal does not allow further movement.

When the conditions are met, transition is allowed; the signal is set to allow train movement to next section; token leaves the section module; additional token is firing to the place *sectionfree;* and information about leaving the section are sent to connected modules. The purpose of storages in module is keeping data about section state. Data is used in transition processor for imposing logical conditions and for section journey time calculation. There are several types of *storages*: *time, info* and *ceka.* The other type of storages (*sectionstate*) serves for gathering data sent by transitions. These storages have information about the state of signals and sections. During the simulation, data from storages is sent to an external database.

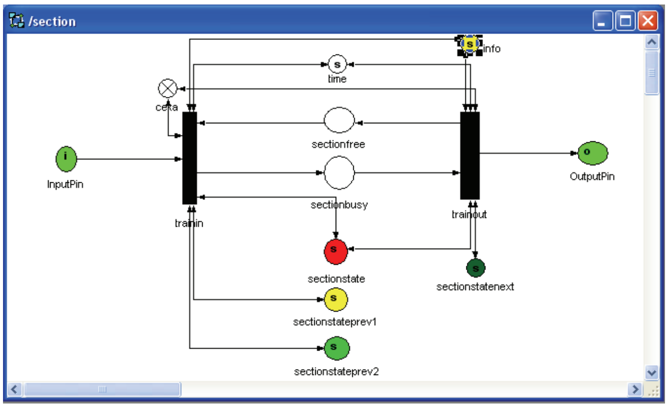

Fig. 1. Module of block section

Modules for other specific sections are similar to those already described, with difference in implementation of the train traffic rules dependent on the location of the section in the system.

After defining the modules, creating the junction simulation model requires connecting modules according to the layout of sections in railway line plan. Then, modules should be connected with storages (Fig. 2.).

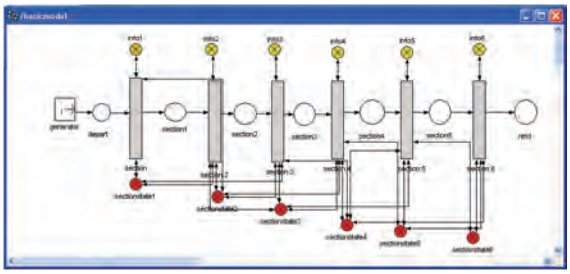

Fig. 2. Creation of the model by connecting section modules

Model is connected to external databases for storing input and output data. Output data is classified and filtered for statistical analysis, as well as for graphical representation of the simulation results. The simulation program gives data about movement of each train through the model, as well as data about section state (total and physical occupancy of each section). The database is customized for creating quick reports based on queries and for filtering data by train, section, signals or train delay time in the model. Data can be presented in tables or graphs, and can be easily validated.

Animation of the simulation run is done in the simulation program itself, animating section states in the model. During the simulation, parameters (from storages) of each section change when a train enters the section. These numerical data are used for animation of sections. Numerical value from storage gives visual identity of the section occupancy symbol in animation window.

III. MODEL FOR GENERATING TRAIN DELAYS BY FUZZY LOGIC

Train delays have great influence on timetable and on technological processes related to train traffic, but also on railways planning procedures. There are primary and secondary delays [6]. Primary delays are timetable disorders caused by disturbed train operation. It is not always possible to avoid primary delays, because of many factors that generate them. Secondary delays are result of “spreading“ the primary delays through the timetable, e.g. transferring the delay factors from one train to the others. Secondary (or knock-on) delays and their propagation are subject to primary delays, railway network structure and train timetable.

Fuzzy set theory is a suitable mathematical approach to modeling processes characterized by subjectivity, uncertainty, ambiguity and imprecision, which makes it a very good tool for modeling timetable disorders (primary delays). Fuzzy logic enables making decisions even when they are based on imprecise information. Models based on fuzzy logic are defined by set of IF-THEN rules. Input variables are linguistic variables which describes current operating conditions for each train. Defuzzified output result of fuzzy inference system is train delay. Values of fuzzy model parameters are defined in collaboration with traffic dispatchers, operators and experts familiar with functioning of the system. Their knowledge and experience, as well as train delay statistics, are used for defining input variables, rules base and output variables.

Fuzzy model is defined with four input variables: train category, timetable influence, train mileage and infrastructure influence (Fig. 3.). The train category and probability of train delay are highly dependent. This is defined with a description from 0 to 10 where numerical scores can be matched by words. The lowest score 0 is given to a freight train (μ_F), score 5 is regional train (μ_R), and score 10 is high category passenger train (μ_P). The membership function for train category is:

$$\mu_F(x)=\begin{cases}1 & x\le 0\\ 1-\dfrac{x}{4} & 0\le x\le 4\\ 0 & x\ge 4\end{cases}\qquad \mu_R(x)=\begin{cases}0 & x\le 1\\ \dfrac{x}{4}-\dfrac{1}{4} & 1\le x\le 5\\ -\dfrac{x}{4}+\dfrac{9}{4} & 5\le x\le 9\\ 0 & x\ge 9\end{cases}$$

$$\mu_P(x)=\begin{cases}0 & x\le 6\\ \dfrac{x}{4}-\dfrac{6}{4} & 6\le x\le 10\\ 1 & x\ge 10\end{cases}$$

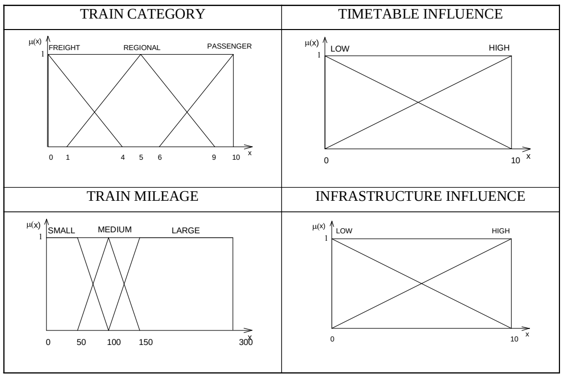

Fig. 3. Membership functions of input parameters

The membership function for output variable train delay (Figure 6) is defined with 5 fuzzy sets: very small (μ_{VS}), small (μ_S), medium (μ_M), high (μ_H) and very high delay (μ_{VH}) (Fig. 4.).

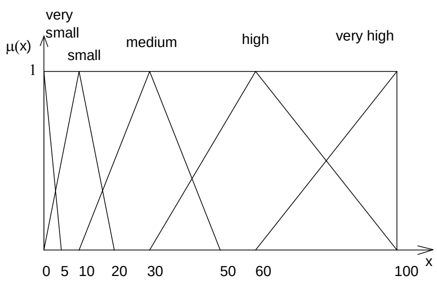

Fig. 4. The membership function of fuzzy set of output variable (train delay)

Fuzzy logic system comprises of 36 rules. These fuzzy rules translate 4 input fuzzy variables into 1 output fuzzy variable. Logical AND operator is employed (the rule of minimum for AND relationships, the so-called Mamdani rule of minimum). In creating the consequent fuzzy set, MAX – MIN inference is used. Defuzzification of the output fuzzy variable is by center of gravity method (COG). Fig. 5. shows relationship between train delay and selected input variables: train category and train distance.

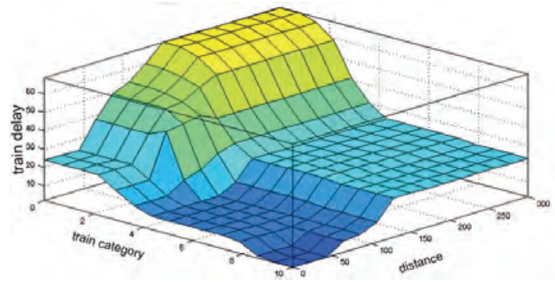

Fig. 5. Relationship between input and output fuzzy variables

Fig. 6. presents an example of fuzzy inference system of model. Test case is for following input parameters:

- train category – 5 (regional train);
- timetable influence – score 4;
- train distance traveled – 40 km;
- infrastructure influence – score 2.

Four rules are related to this set of input data: rule 13, 14, 19 and 20. Defuzzified output variable gives calculated train delay: 7.15 minutes.

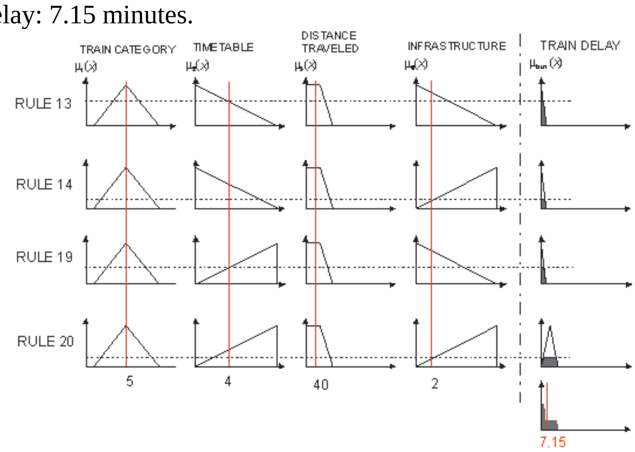

Fig. 6. Example of fuzzy inference system

IV. PETRI NET MODEL EXAMPLE

Junction G in Belgrade railway node is chosen as an example of the Petri Net simulation model. It is a complex double-track diamond crossing junction. The boundaries of the model are stations Belgrade Center, Topcider, Rakovica and Karadjordjev Park. Model is defined with data from section and railway signals layout plan, as well as from timetable for year 2008.

Petri net Model of the junction G is shown in Fig. 7.

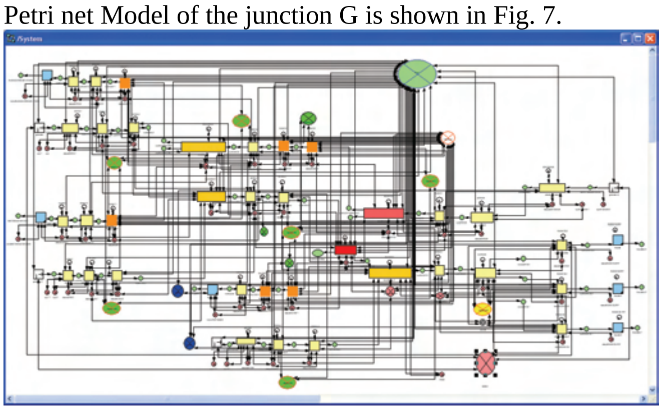
Fig. 7. HLPN model of railway system (part of Belgrade Node)

The simulation can be observed by viewing:

- token movement through the Petri Net Graph,
- storage state indicators and
- animation window which shows the state of each section in the model.

The model allows experimenting by inserting new tokens in *places* during simulation (marking of a Petri Net model). After the simulation, the results can be viewed in the external database and subsequently edited in the form of reports, graphs, sketches, and tables.

Verification and validation of Petri Net junction model

Validation and verification of Petri Net simulation model can be done by:

- monitoring if tokens movement is according to operating rules;
- inspecting storage indicators;
- animation window which shows the state of each section in the model (Fig. 8.);
- data analysis. Simulation results are stored in database where reports can be generated.
- Train time–distance diagram generated from simulation results (Fig. 9.). Any irregularities and conflictsituations in model can be easily identified on a train diagram.

Fig. 8. Animation window indicating state of sections

Animation window is modeled to visually resemble to dispatcher interlocking control panel. Sections of model are animated by using section state data located in storage.

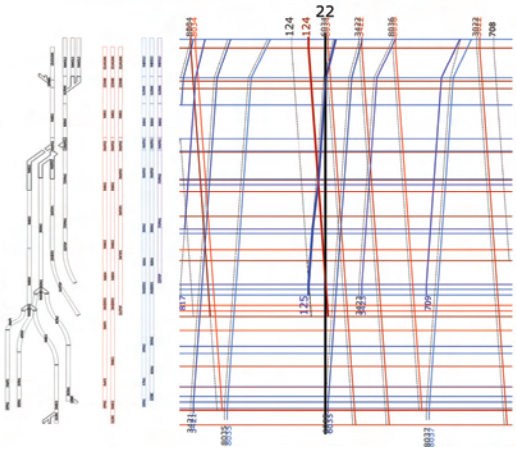

Fig. 9. Time - distance graph of train simulation

V. Results of a Petri Net model

Results can be classified and filtered for analysis in external base that collects simulation data. Multiple queries can be used to generate reports. Reports can assist at timetable analysis, analysis of train delay by train category, by section etc. Database can generate reports for comparing results of experimenting with model by changing timetables, section layout, junction design or introducing new train operating rules policy.

Average section occupancy data can indicate possible bottlenecks of system (Fig.10.)

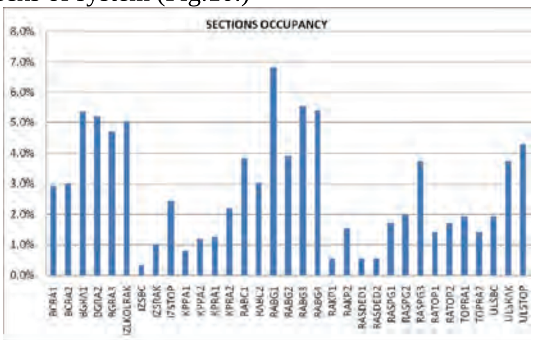

Fig. 10. Percentage occupancy of sections in model

Sections with highest percentage of physical occupancy are sections between junction and stations, and their occupancy is highest because of their length. Fig. 9. shows a part of train time – distance diagram for sections of a model. Dashed line present train routes by timetable and continuous line (colors represent different train categories) represent train routes with supplemented primary delay calculated in fuzzy logic system

Simulation results could be utilized for:

- decision making in investment projects,
- testing infrastructure or technological design of junction, station, sidings, etc.,
- analyzing effects from experimenting with train operation rules,
- analyzing timetables,
- testing railway line capacity,
- analyzing train delays.

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