# THE METHOD OF NESTED SIMULATIONS SUPPORTING DECISION-MAKING PROCESS WITHIN A MESOSCOPIC RAILWAY SIMULATOR

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**ABSTRACT**
While executing stochastic simulations, some unexpected (conflict) situations may occur thanks to which it is not possible to continue with the simulation in appliance to prescribed rules and it is necessary to decide on an alternative solution. There is a variety of tools for supporting the decision-making activities – methods of operational research, heuristic methods, etc. Another method is based on nested simulations with which the solution of a problem is searched using recursive simulations making a limited outlook into the future. At the moment when the problem occurs, alternative scenarios are created and simulated. After a certain period of time the nested simulations are stopped, their results are evaluated, the most suitable solution is selected and then the simulation continues in compliance with that solution. This contribution describes the issue of decision-making support in simulators, and it focuses mostly on the description of the method of nested simulations.

Keywords: nested simulations, decision-making support, railway transport

## 1. INTRODUCTION

Our research is focused on the class of transport, service, and logistic problems – main attention is paid to the area of railway transport, which has been our primary interest for a long time. Within railway transport we focus on investigating railway yards and junctions with the help of an experimental method of simulation. Exploiting simulations enable (i) to examine the current status of the infrastructure and its usage (using the same traffic flows), and (ii) to find out what results the alterative scenarios bring. Such scenarios can be represented not only by different track layouts, but also by a different structure of traffic flows (following relevant timetables). Thanks to simulations we can examine in great detail the behaviour of different traffic flows without having to apply such changes in reality. Thus, computer simulation represents an appropriate approach of examining railway systems.

## 2. SIMULATING RAILWAY TRAFFIC

It is possible to use various approaches and methodologies to examine, analyse, and optimize railway traffic. One issue of our interest is the examination of railway station capacity (throughput), i.e. to quantify the usage of tracks or switch zones with regard to a given traffic scenario (timetable) and to find potential bottle necks.
The capacity of a railway infrastructure can be determined in three ways: (i) by analytical methods, (ii) by graphic-analytical methods, (iii) by experimental methods, or (iv) by combination of any of the aforementioned methods. Analytical, or graphic-analytical, methods are specified for example within directives D24 (SŽDC, 2009) or UIC406 (ETF, 2013). Those methods mathematically analyse the usage of individual parts of rail infrastructure (using a special indicator called *degree of occupancy*. Alas, such methods do not enable to flexibly react to stochastic phenomena and therefore it is more appropriate to apply the experimental method of computer simulation.
Simulation can use a deterministic approach (without the application of random effects), or a stochastic approach enabling the occurrence of random influences (e.g. train delays). Randomness in railway traffic can influence the overall situation greatly – rail infrastructure is limited by the number of tracks and signal and interlocking systems, so it is not possible to immediately send delayed trains to currently occupied tracks. Thus, delays can negatively influence a quality of rail traffic.

## 3. DETERMINISTIC VERSUS STOCHASTIC SIMULATIONS

Deterministic simulations are such simulations that do not include random inputs. A simulation trial can be repeated and its results can be exactly calculated. Deterministic traffic simulations reflecting systems of railway stations expect that all trains are on time, there are no unexpected closures, delays, or other non-standard events.
Stochastic simulations bring an element of indefiniteness to the progress of simulation trials. Thus, at least one of the inputs is supposed to imitate random influences. For that purpose pseudorandom number generators are utilized. Considering stochastic inputs,

the following phenomena in rail traffic simulations can occur: (i) random delays related to train arrivals, (ii) technical failures connected with trains or technical devices, (iii) arrivals of non-scheduled trains, etc. Let us mention an example of typical operational conflict situation involved within stochastic simulations: it is scheduled an arrival of train $T_1$ at the platform $k$, a considerably delayed train $T_2$ is expected to approach the station at the moment $t$ and it is also supposed to stop at the platform $k$, which is currently occupied.
Such collision situations can be solved in two ways: (i) within an *interactive mode* (a solution if formulated by the user), or (ii) using an appropriate technique of *automated decision support*.

## 4. DECISION-MAKING SUPPORTS WITHIN SIMULATION MODELS

Decision-making support in a simulator (applied during a simulation trial) can utilize a collection of methods or routines called at the occurrence of a conflict situation. The results of those methods should offer a relevant solution concerning how to proceed with the simulation experiment. There is a variety of techniques that can be used for decision-making support - such methods include:

- interactive mode of simulation,
- the method of priority planning,
- expert systems,
- methods of operational research,
- heuristic methods,
- methods of soft computing,
- methods of nested simulations etc.

### 4.1. Interactive mode of simulation

Interactive mode of simulation does not represent a method of automatic decision support. When a conflict occurs, the simulation is interrupted and the user is asked to define a solution. That approach enables to train users in various areas. Based on the user's inputs, the state space changes and the results are usually displayed online.
On the other hand, long-term simulations with a large number of replications and the high number of conflict situations are usually not good candidates for applying an interactive problem solving.

### 4.2. Priority planning

Priority planning represents a simple way of producing automatic decisions with regard to conflict situations. Before executing a simulation trial, a priority queue of possible alternative solutions is created for conflict situations. When a conflict situation occurs, the solution with the highest priority is chosen. If such a solution is not applicable, other solution is chosen based on its rank of priority until the entire priority queue is traversed. That method can be adapted for various situations (e.g. a list of alternative platform tracks for delayed passenger trains etc.).

### 4.3. Expert systems

Expert systems involve a group of computer programmes with the aim to provide expert advice based on using specialized routines directly developed for a certain kind of decision-making support. There are two types of expert systems, *diagnostic* ones and *planning* ones. In contrast with conventional programmes, the knowledge of expert systems is stored separately from their data, and their inference mechanism, that manages the expert system, can be based on various principles - assessing logic rules, fuzzy logic, artificial neural networks, etc. Expert systems also contain an explanatory sub-system capable of substantiating why the selected solution is the right one.
The aim of expert systems is then to substitute an expert in solving various problems using a computer programme. After the data specifying the current situation are put in, the inference mechanism is run and it calculates the solution to the problem in cooperation with its knowledge base.
Nowadays many authors deal with using expert systems being interconnected with simulations. The connection of simulation models and expert systems can be found in Masmoudi, Chtourou, and Maalej (2007). The issues of creating an expert system using simulations are discussed in Li, et all (Li, Li, Li, and Hu, 2000).

### 4.4. Methods of operational research and soft computing

Operational research represents a vast field dealing with various tasks and optimization issues. Tools for solving mono-criterial (so called linear programming) or multi-criterial issues belong to the field. For multi-criterial evaluations of variants, on the input there is a set of criteria influencing the quality of the solution based on various characteristics. Setting up particular values of the criteria then significantly affects the given results. There is a variety of methods of fixing those values, for example *pairwise comparison method*, the *Saaty's method* etc.
Other methods focused on finding solutions to optimization problems and realizing decision support are based on heuristic approaches. *Heuristic methods* reach relevant solutions faster than exact methods. However, their solutions are not guaranteed to be optimal (suboptimal solutions are acceptable – especially in cases if the solved task is connected with non-polynomial complexity).
The term *soft computing* includes a set of computational methods - *fuzzy logic, artificial neural networks, genetic algorithms*, and *probability calculations*. All these methods provide the potential to solve immensely complex tasks by means of fairly easy mathematical apparatus. Individual methods might not provide the optimal solution and their quality depends on their particular implementations and appropriateness for a given kind of a solved problem.

### 4.5. Nested simulations

*Nested*, or *recursive simulation* represents another methodology applicable for the needs of decision-making processes. The principle of that method is based on interrupting the *main simulation* when a conflict situation occurs and then the main simulation is cloned. Individual clones (*minor simulations*) are parameterized in such a way that various options of solutions are tested. Such nested/recursive simulations (different outlooks into the future applying a limited time horizon) are run and after a certain time period it is assessed which minor simulation shows the best results. Then the main simulation continues only with "the best" selected option. Despite the fact that the principle of nested simulations is simple and it uses a versatile simulation engine for finding solutions, several crucial technical issues have to be figured out.

## 5. THE METHOD OF NESTED SIMULATIONS

The method of *nested*/*recursive simulations* is based on the principle of using simulation trials inside a main simulation run in order to examine the results of several alternative simulation scenarios. The main instance (trial) of simulation is cloned and individual clones (minor/alternative trials) are parameterized differently. The method of nested simulations provides executing several alternative scenarios in parallel. The results of nested simulations present a broader set of solutions to the given problem.

One possible application is connected with decision-making support within simulating systems. Nested simulations are being simulated for a limited time period, their results are assessed, and the minor simulations are joined again into one instance. Then the main simulation can continue with the selected solution. That approach we apply within the frame of our research.

Another application of nested simulation is related to *multi-trajectory simulation* - a simulation experiment is divided into nested trials in critical points, and subsequently those trials can be increasingly nested. According to Gilmer and Sullivan's (1999), such a procedure is more efficient than using a higher number of replications of one simulation experiment.

### 5.1. The technique of nested simulations

Nested simulations allow using (i) an existing simulation engine and (ii) several simulation trials for searching solutions of occurred problems. Let us introduce a relevant procedure focused on solving critical/conflict situations:

1. A conflict situation (requiring an appropriate decision) is identified during simulation.
2. Current instance of the main simulation ($S^{main}$) is interrupted at the time *t*.
3. For the needs of nested simulations, it is necessary to set their parameters:
   a. The criterion of optimality (*CrOpt*).
   b. The duration of an outlook into the future for the nested trials (or rather the stopping condition - *StopCond*).
   c. The number of replications for all individual scenarios of nested simulations - *ReplCount*.
   d. The number of alternative scenarios (minor simulations) - *ScnCount*.
4. *N* alternative scenarios for minor simulations are established.
5. The main simulation $S^{main}$ is cloned and *ReplCount* of replications is created for each *i-th* scenario ($i = 1 \ldots N$).
6. Individual replications $S_i(j)$ are started (for $i = 1 \ldots N$, $j = 1 \ldots ReplCount$).
7. Waiting for finishing all replications $S_i(j)$ (for $i = 1 \ldots N$, $j = 1 \ldots ReplCount$).
8. Assessing the results of individual scenarios from the replications $S_i(j)$ (for $i = 1 \ldots N$, $j = 1 \ldots ReplCount$) and then selecting the scenario with the best results according to *CrOpt*.
9. The main simulation $S^{main}$ then continues with the selected scenario from the instant *t* of simulation time.

The above mentioned procedure is illustrated in Figure 1. Certainly the problem how to define alternative scenarios for solving conflict situations represents a non-trivial problem which will be discussed in the full contribution.

### 5.2. Brief overview of the state-of-the-art

It has to be declared that not many authors pay attention to the research of nested/recursive simulations.

The authors Gilmer and Sullivan were focused in several of their articles on the efficiency of higher number of replications in contrast with multi-trajectory simulation (Gilmer and Sullivan, 1999). Their main interest is related to the military simulator Eaglet, which simulates the movement of military units of two armies and their mutual interactions.

Eugen Kindler (as a pioneer of nested simulation in Europe) published many articles with the focus on both, the theoretical description of nested simulations (classification, terminology, etc.) and their applications in practice (Kindler, 2010).

The issue of a planning support system is discussed by Hill, Surdu, Ragsdale, and Schafer (2000). Those authors were engaged in military planning.

Another area of applied nested simulations is connected with scalable simulation models, which allow applying both a macroscopic and a microscopic level of investigation within the frame of one simulator (Bonté, Duboz, Quesnel and Muller, 2009). Another area of exploiting nested simulations is financial a risk management – e.g. Gordy and June (2010).

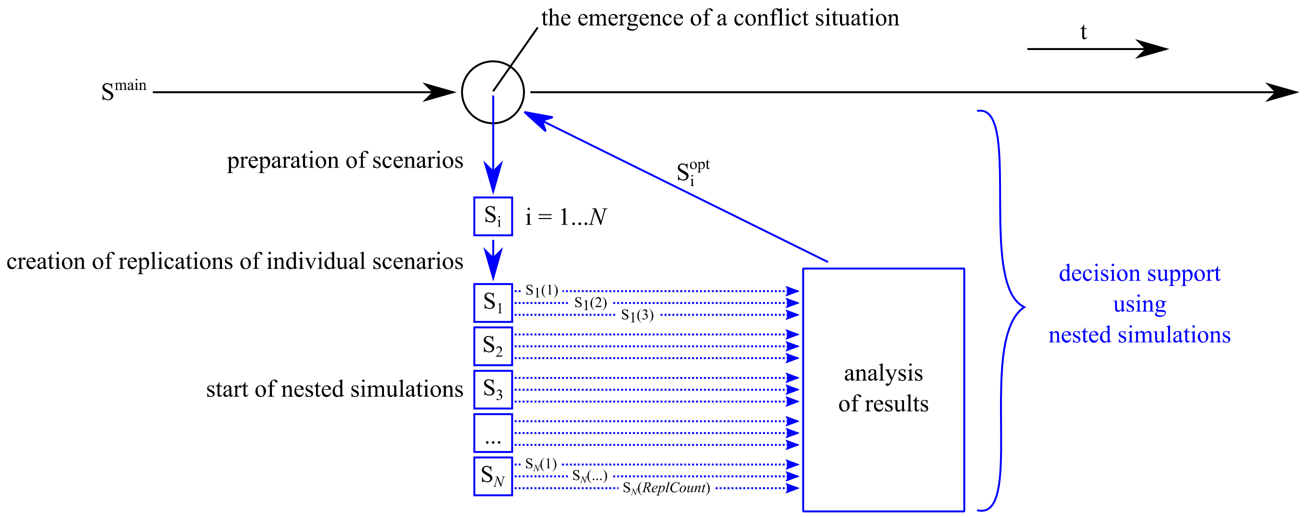


Figure 1: Illustration of one replication belonging to the main simulation - occurrence of one conflict situation is depicted

## 5.3. Executing nested simulations

Before the execution of nested simulations, it is necessary to fix a set of parameters. That set can differ depending on the type of the conflict situation that has occurred.

The first parameter specifies the number of alternative scenarios (or rather their minimal and maximal permissible count, *ScnCount*), which determines how many various alternatives will be examined in the nested simulations.

For every alternative scenario it is necessary to get statistically processed results (based on the outcomes from *ReplCount* replications). Individual nested simulation trials must be terminated after a certain period of time in order to assess their results. Stop condition *StopCond* dictates after what elapsed simulation time (or under which conditions) the nested simulations will be terminated. After terminating all nested simulations, their assessment is carried out.

The last parameter is the criterion of optimality (*CrOpt*) – that function evaluates the results of individual scenarios, which were executed as nested simulations and it selects the scenario providing the best solution. The main simulation then continues using the selected scenario.

### 5.3.1. Computational complexity

A separate and complex issue of nested simulations is related to applicable implementation techniques. Implementations are connected with potential time-consuming computational tasks that are influenced by the numbers and lengths of executed simulation trials. Thus, overall computational complexity is influenced by several factors:

- the number of alternative scenarios,
- the number of replications,
- the lengths (time durations) of replications,
- the number of conflict situations that occur in the main simulation and which require making decisions based on the outlooks of nested simulations,
- the number of replications of the main simulation.

Apart from these factors, it is also necessary to consider the possibility of occurred conflict situations within the nested trials. Such a phenomenon can cause recursive run of other nested trials and cause in fact an exponential growth of the problem complexity. One way how to avoid such a problem is to terminate the nested simulation exactly at the moment when a conflict situation occurs inside it. That approach will be considered in our case study.

Executing a large number of nested simulations can take a lot of time even if the modern computers are utilized. The individual nested simulation trials do not affect each other and therefore they can be executed in parallel. A simple way is to execute the calculations in separate processes or threads and allow the nested simulations to use more processor cores within one computer. The most demanding tasks can allocate relevant computation on the GPU or use parallel processing on more computers (either within a distributed grid structure or a cloud).

Allocating computations into more processes, threads, or computers means that the simulator must be able to save the status of the simulation, copy it, and then prepared it for further parallel processing. For distributed methods (grid/cloud) it is then necessary to select a suitable way of data transfer and synchronization - shared file storage, communication over network sockets, etc.

## 5.4. Case study

Our research focus is related to traffic simulations mainly reflecting railway systems. Hence, an application of nested simulations as a decision-making support within the above mentioned kinds of simulators was chosen to be tested.

### 5.4.1. Simulation tool MesoRail

The simulation tool *MesoRail* (Diviš and Kavička, 2015) is a mesoscopic simulator of railway traffic, which focuses on examining traffic characteristics of railway stations on a mesoscopic level. The mission of that simulator is to allow processing simulation studies in shorter time than it is usual with the help of simulation tools applying a microscopic level of details. Our current research is concentrated on decisions about assigning substitute platform tracks to delayed trains. The appropriate decisions are supposed to be taken with the help of nested simulations.

The method of nested simulations was selected because of several reasons. The first reason is the ambition to use the tested simulation engine as a tool participating in decision-making processes. Another reason is that the principle of nested simulations allows simulating potential traffic progress directly, thus the results of the selected scenario are immediately transparent, and the best solution is then selected.

### 5.4.2. Simulation scenario

The problem of assigning substitute platform tracks was selected as a case study of deploying nested simulations as an automated decision support in a simulator. In stochastic simulations, there are delays occurring for individual trains (upon entry to the simulator and during the simulation itself) and thus conflict situations may arise. Standard platform track for an arriving train can already be occupied and so the role of the decision support is to select a substitute platform track. The selection of a substitute track also affects the situation in the station and it can cause more conflict situations. The decision support algorithm should ideally minimize the subsequent conflicts and it should also keep the station throughput at maximum.

Our goal was to apply and test the method of nested simulations. The method of priority planning was selected as a competitive method. A list of alternative targets (tracks in the station) was defined for each train route. During the run of the simulation, an available route with the highest priority is automatically selected. The priorities are static and fixed for all simulation experiments.

The parameters of the nested simulation method were selected as following:

- optimality criterion – the total of delays for all trains in the simulation,
- the number of replications of nested simulation – 1
- the number of alternative scenarios – maximal possible number given the situation,
- the time duration of the nested simulation – 5 minutes,
- the possibility to conduct recursive nested simulations – no.

For the first experiments with the nested simulations method, we created a small infrastructure of a railway station – 5 platform tracks, 2 passable station tracks, and a double track leading from east to west. The default scenario includes freight and passenger trains arriving to the station in a 10 minute interval from both directions. Occupancy of platform tracks for a given timetable is depicted in Figure 2.

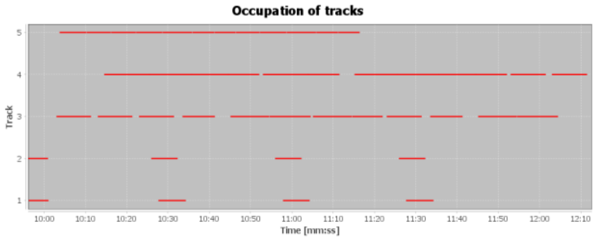


Figure 2: Occupation of tracks in the case study simulation scenario

To assess the quality of the decision support, stochastic simulations were conducted - the trains were assigned a random delay on the point of entry into the simulation. Exponential division of probability of the average of 5 minutes for passenger trains and the average of 15 minutes for freight trains was selected.

Then, a series of experiments was conducted: (i) without delay, (ii) with delay only for passenger trains, (iii) with delay for all trains. To assess the quality, the total of delay of all trains in the simulation was used as a criterion. Example of running nested simulations within *MesoRail* simulator is shown on Figure 3, four nested simulations are trying to find replacement station track for delayed incoming train. The results of individual experiments are illustrated in Table 1.

To conclude from the shown results, the method of priority planning showed the best results for the conducted case study, second best was the nested simulations method, and the longest delays occurred without decision support (in this scenario, trains wait for the original station track to be vacant). Alternative II shows a great difference between both methods; the method of priority planning effectively used vacant station tracks. Nevertheless, the method of nested simulations does not show such great results for the selected parameters. Alternative III depicts a more complex situation in which all trains have been assigned a delay. The method of priority planning again shows the best results, method of nested simulations is in second place, differences between both methods remains nearly similar.

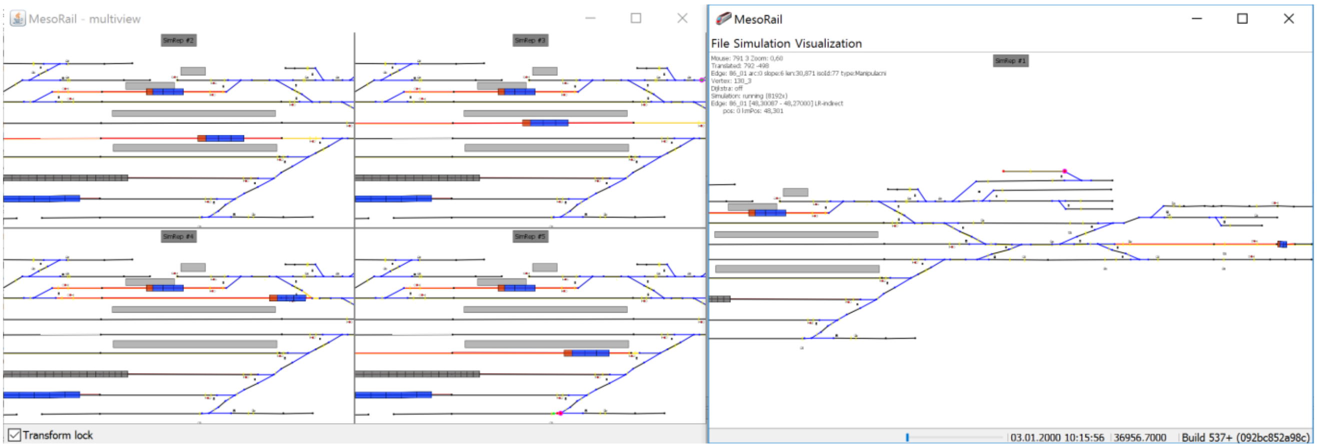

Figure 3: Running main simulation with four nested simulations (on left side of image)

Table 1: Results of simulation experiments

| Scenario | Method | Average value of sum of delay additions | Minimum | Maximum |
|---|---|---|---|---|
| I | no decision support | 100,0 % | | |
| | priority planning | 97,2 % | | |
| | nested simulations | 98,2 % | | |
| II | no decision support | 124,8 % ± 14,7 % | 103,7 % | 151,4 % |
| | priority planning | 94,4 % ± 12,0 % | 71,8 % | 112,0 % |
| | nested simulations | 111,2 % ± 16,4 % | 85,4 % | 134,5 % |
| III | no decision support | 131,3 % ± 20,6 % | 94,9 % | 159,4 % |
| | priority planning | 97,5 % ± 14,2 % | 79,1 % | 117,8 % |
| | nested simulations | 121,1 % ± 11,7 % | 100,2 % | 138,8 % |

## 6. CONCLUSION

The issue of solving conflict situation in stochastic simulations was introduced in this article. Such situations can be solved manually or automatically by using a decision support based on various methods. Next, the method of nested simulations, which uses nested simulations to find the best solution, was introduced. The method of nested simulations was implemented into the Mesoscopic simulation tool *MesoRail* and tested on a case study. The results of the method were compared to the method of priority planning. From the collected data it is obvious that the method of priority planning now shows better results than the method of nested simulations. Nevertheless, the method of nested simulations offers a wide variety of parameterization and application. In the next development phase of the *MesoRail* tool, the effect of various parameter combinations on gained results will be tested further. An interesting yet very complex and computationally demanding task is the option to perform recursive nested simulations and thus search for an optimal solution in great detail. Using such approach with an appropriate selection of parameters should allow to gain even better results than with the static method of priority planning.

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