Sensitivity analysis applied to multiline traffic rescheduling in case of electrical power failure

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Abstract

The present work addresses rail traffic rescheduling in case of electric infrastructure failure. The power available for train traction is restricted and the traffic should be reorganized according to this constraint. The system behavior is analyzed by simulation, using a dynamic multi-physics railway simulator that gives physical quantities such as train's speed profiles, voltage along the catenary lines, heating's…The rescheduling problem relies on this black box model, with a large number of input variables, constrained dynamic outputs (typically voltage limits). It involves a complex simulator and a high computation cost. We propose a rescheduling process based on regional sensitivity analysis. Monte Carlo filtering and the two-sample Kolmogorov-Smirnov test statistics are used in order to analyze which rescheduling actions are efficient to obtain an acceptable traffic (respect of operational constraints).

Our methodology allows to identify important inputs and reduce the problem's dimension. Non-influential variables are set to a fixed value, and an optimization post treatment can be performed with the remaining influential variables and performance indicator defined by the operator. This analysis allows the decision maker to choose the solution which best fits his objectives. The proposed approach has been tested on a multi-line heterogeneous traffic. The considered incident is a loss of feeding power substation.

Keywords: rescheduling, sensitivity analysis, optimization, electrical failure, decision-making.

1. Introduction

The issue of railway traffic rescheduling in case of an undesirable event is becoming more important with traffic increase. Events such as bad weather, technical failures or accidents may cause a disturbance or a disruption, depending on their influence on railway system. Disturbances are defined as small perturbations of the timetable and happen when a single train delay affects a large number of trains due to cascade effects. In contrast, disruptions are large perturbations due to infrastructure or rolling stock failures that significantly influence train operations on railway network. Disturbance and disruption management are currently active research areas in operations research.

Until recently, most research about train rescheduling was dealing with disturbances and delay management [1], [2] [3], [4]. As a consequence, the literature that has addressed the subject of timetable adjustment during disruptions is limited. Most often, authors discuss impact of unavailability of one or several tracks during a certain time period. A complete blockade corresponds to a situation in which all tracks of certain segment are blocked, which prevents any train to circulate on that segment. In the case of a partial blockade, only some of the tracks are blocked and limited traffic is still possible. In [5], authors consider the problem of rescheduling timetable in case of a partial and a complete blockade. They propose an integer programming formulations, where rescheduling actions are delaying trains, cancelling trains and reversing trains at stations adjacent to the blockade. The method is applied to a small two line network in the Netherlands. In [6], the same type of method and network are considered and authors focus on short-turning management in case of total blockade to minimize the total weighted train delay and number of cancelled trains, whereas in [7], authors consider a high speed line in China, with a complete blockade but no reversing train action. The paper [8] develops a mixt integer linear programing model that detects and resolves conflicts in the case of a single track bidirectional line, with a complete temporary blockage. Disrupted trains are rescheduled in both directions of the line, with the objective of minimizing the total delay of all trains. In [9] and [10], the overall passenger disutility is added to the operational costs. An adaptive large neighborhood search meta-heuristic and a metaheuristic are proposed for faster rescheduling and multi-objective optimization including: deviation from the undisrupted timetable, low operational cost, and acceptable passenger service. The readers can refer to [11] for an overview of recovery models and algorithms for real-time railway disturbance and disruption management. For in-depth reviews of this literature, we refer to [12] and [13] for recent surveys on train timetabling problems.

The present work addresses train traffic disruption due to an electrical infrastructure failure, for example a feeding substation out of order. In such a case, the electric power available for moving the trains is reduced and the traffic needs to be adapted: fewer trains can travel at the same time, and they may have to be slowed down. This can be handled by rescheduling variables such as train delays, but also speed profiles. Unlike other researches, this numerical model is complex and nonlinear, which prevents the use of linear programing and it requires simulation to check the availability of power. When searching the literature, we did not find any paper dealing with this type of problem. We propose a method based on regional sensitivity analysis in order to rank the influence of the adjustment variables while accounting for various operational constraints. Our rescheduling methodology introduces a strategy that will help the decision-maker to choose an optimal solution according to various criteria for reorganization the railway traffic.

The paper is organized as follows: Section 2 describes the problem; Section 3 introduces generalized sensitivity analysis and presents how the method is applied to traffic rescheduling; Section 4 provides a test case and results and Section 5 concludes.

2. Problem statement

The electrical infrastructure of a railway network is designed and controlled so as to provide the power needed by the trains. It is a complex system, in which the main elements are the feeding sub-stations, the catenaries, the rails (return conductor) and the trains. Other devices allow to configure the electrical network's topology according to the needs. Numerous trains travel at the same time on different lines, and the analysis of the system relies on simulation.

2.1 Simulation tool

The simulator calculates all the physical quantities that interest the engineer, for given infrastructures and traffic instructions. In the present work, we use ESMERALDA NG [14], the software developed by SNCF Reseau. This simulator is based on a multi-physical model of the railway network: mechanical, electrical, and thermal. The input data are the physical description of the railway network on one hand (topology, position and characteristics of all devices, including the trains) and the description of the intended traffic on the other hand (type of trains, departure and passage times at various points, and reference speed profiles along the way). The equations of train dynamics are coupled with the circuit equations of the electrical network and solved step by step over time in order to determine the position of the different trains at each time, as well as different electrical quantities such as the voltage at the pantographs, powers passing through catenaries and transformers and the resulting heating (**Fig. 1**).

For example, trains are scheduled to leave at given times, and travel according to a certain speed profile. If a component of the electrical infrastructure is unavailable, due to either a technical incident or a maintenance operation, the power available for traction is reduced, and then the train traction power is automatically reduced. It is then necessary to check if the residual capacity allows to maintain the traffic initially planned. From a technical point of view, the quality of power distribution is monitored through the catenary voltage: a too small value indicates that the electrical network is overloaded, and requires the traffic to be adapted according to the power supply capacity. In the present work, four operational constraints are considered: catenary voltage, substation and cable heating's and power of substations, which must remain within the range defined by the standards. If not, the train traffic must be rescheduled.

2.2 Adjustment actions

Reorganization is about making changes in the traffic instructions, in order to diminish the load of electrical infrastructures so that operational constraints are fulfilled. These changes are called adjustment actions and denoted by (X). The adjustment actions proposed to the operator in context of a search for a feasible solution are as follows:

1. Increase of time interval between trains,
2. Speed reduction around positions where the voltage is too low.

Other adjustment actions can be added, such as reducing the auxiliary power or postponing starting times to avoid crossing between trains. This will enable experts to choose actions as necessity arises.

The goal of reorganization is to determine which adjustment actions are needed in order to obtain an acceptable traffic. (**Fig. 1**) represents the structure of the adjustment model. It is a nonlinear, time consuming numerical model with a large number of inputs and dynamic outputs.

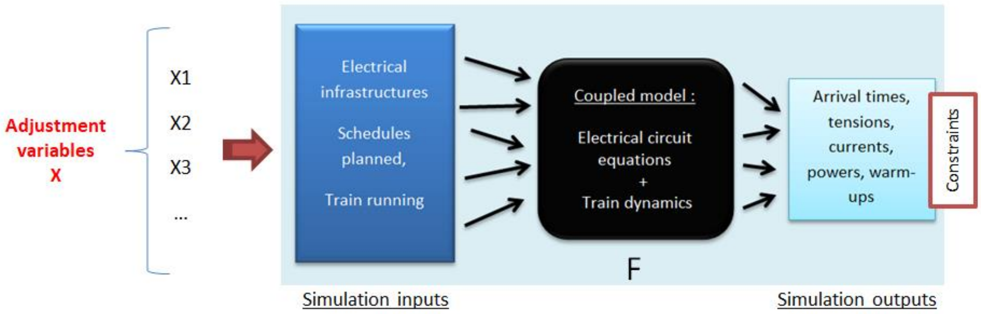

Fig. 1: Structure of the adjustment model.

3. Methodology

In the current situation, traffic rescheduling is carried out according to an iterative trial-and-errors method: based of their experience, operators propose re-planning solutions and run simulation to check if the catenary voltage remains within the prescribed limits. This process is slow because the analyzed situation is complex (many trains, many lines) and numerous simulation runs are needed. Furthermore, the outcome of the process, both in terms of quality of the solution and time to reach it, fully depends on the operator experience and know-how. There is no guarantee that an optimal solution will be reached. The goal of the presented work is to assist the operator in the rescheduling process thanks to sensitivity analysis. Sensitivity analysis is used for a better understanding of the problem and answers questions like: which adjustment operation is the most influential? Which traffic adjustments are needed to reschedule the traffic while respecting operational constraints? Capturing which adjustment actions are important in order to respect constraints is a key information for a rescheduling tool.

3.1. Regional sensitivity analysis

We are interested in determining which input values lead the model output in an acceptable region, defined by the respect of operational constraints. For this, we use regional sensitivity analysis, based on Monte Carlo Filtering [15]. Monte Carlo runs are performed and the sampled input space is partitioned into two groups, depending on whether the associated model output satisfies or not the desired condition. The so-called « Behavioral group », denoted by (B), of size n, contains the elements that respect the performance indicators, while the « Non-behavioral group », denoted by (NB), of size $\overline{n}$, contains those that do not. The sum $n + \overline{n}$ corresponds to the total number of runs.

After the sets of acceptable and unacceptable samples have been identified, the sensitivity to a given input parameter can be calculated by comparison of their statistical properties. The cumulative distribution functions of both groups, respectively denoted by $F_n(B)$ and $F_{\overline{n}}(NB)$, are computed for each input Xi (**Fig. 2)**. Then the two sample Kolmogorov-Smirnov test is used to quantify the difference between $F_n(B)$ and $F_{\overline{n}}(NB)$. This test is based on the parameter d, defined by:

$$d = \max_{X_i} |F_{X_i|B}(X_i|y \in Y_B) - F_{X_i|NB}(X_i|y \in Y_{NB})|$$

The statistic d represents the maximum distance between the two cumulative distribution function curves. If this distance increases, the influence of Xi increases as well.

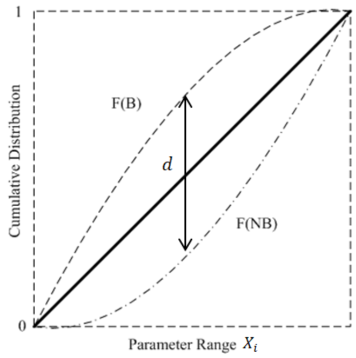

Fig. 2: Comparison of cumulative distribution functions for behavioral subset and non-behavioral subset of parameter Xi.

3.2. Rescheduling Approach

In case of incident on an electrical infrastructure we look for a reorganized traffic which respects all physical constraints (pantograph voltage levels, heating of cables …) and will be adapted to the traffic capacity and might be complying with certain criteria. The proposed tool automates calculation of this search and it involves four main stages (**Fig. 3**):

a) *Problem specification*: the decision-maker defines the traffic adjustment variables, their range of variation, the output performance indicator that defines the set of acceptable solutions, and the criteria used to generate optimal solutions.
b) *Simulation runs of Monte-Carlo type*: the processor generates N quasi-random samples according to adjustment actions defined in stage a) and runs the corresponding simulations.
c) *Sensitivity analysis phase*: sensitivity analysis is applied in order to explore the space of feasible solutions and to assess the impact of the different adjustment actions.
d) *Post treatment and optimization phase*: optimization is performed within a smaller search volume. *Finally* the decision-maker can choose a solution associated to an adjustment scenario from the set of optimal solutions according to his objectives.

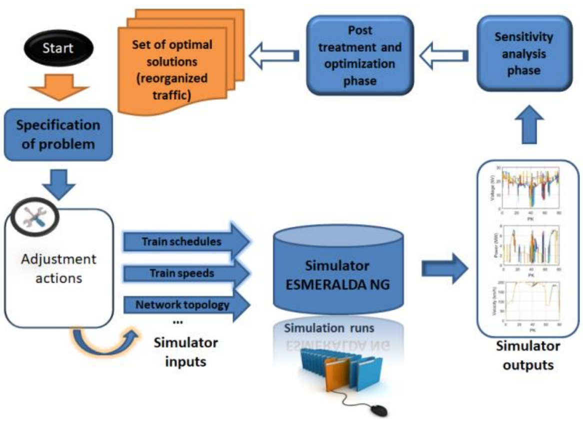

Fig. 3: graphic illustration of the tool

4. Test case and results

The test case corresponds to a multi-line heterogeneous traffic (TGV, TER, FRET), fed by 100 sub-stations in DC mode. The studied incident is total loss of two substations (at 60.760 Km and at 69.159 Km) that supply line 9. Operational constraints are not respected; hence traffic must be reorganized.

Ten adjustment actions are defined to adjust the time interval between train departures, and two adjustment actions consist in reducing the train speed around the damaged substations.

4.1. Results of sensitivity analysis

The sensitivity analysis method presented in this document has been applied with 1000 quasi-random samples. The adjustment actions are classified between "Important" and "Unimportant" actions in reorganization process as show the Table 1**.**

Table 1: Results of Regional sensitivity analysis.

Adjustment action	*Sensitivity index*	*Signification*
Action1 (TER, Line 9, Track 3)	0.07	Unimportant
Action2 (TER, Line 9, Track 1)	0.14	Important
Action3 (TGV, Line 9, Track 1)	0.04	Unimportant
Action4 (TER, Line 9, Track 2)	0.14	Important
Action5 (TGV, Line 9, Track2)	0.05	Unimportant
Action6 (FRET, Line 9, Track2)	0.06	Unimportant
Action7 (TER, Line 9, Track4)	0.07	Unimportant
Action8 (TER, Line 13-Line9)	0.1	Unimportant
Action9 (TER, Line 12-Line 9)	0.43	Important
Action10 (TGV, Line 12)	0.06	Unimportant
Action11 (speed reduction 60-70 Km; Line 9)	0.16	Important
Action12 (speed reduction 70-80 Km; Line 9)	0.08	Unimportant

4.2. Some optimal solutions

Based on sensitivity analysis results, an optimization phase is applied with a new parameter setting, in which only "Important" actions are considered, while "Unimportant" actions are set to zero. Having fewer variables in optimization problem results in a smaller search volume.

- Mono-objective optimization : F1 "Maximize the traffic density" : The optimal solution found is with density = 67.5 trains per hour (nominal density = 72.9 trains per hour). (**Fig. 4)** represents the pantograph voltage levels respected by this solution.

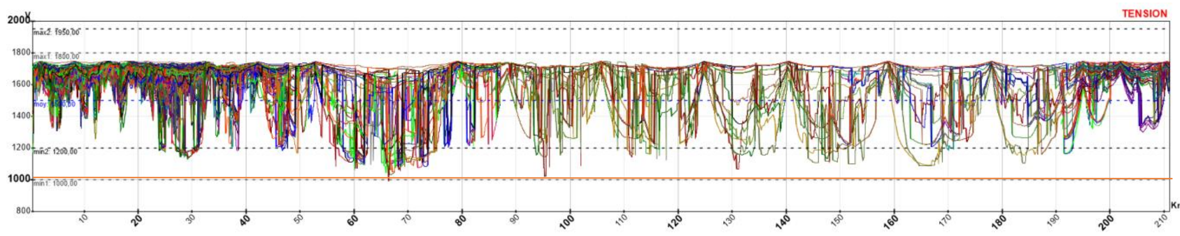

Fig. 4: Pantographs voltage for the solution that maximizes traffic density "F1"

- Multi-objective optimization: F1 "density of traffic" and F2 "substation heating's": **(Fig. 5)** shows a Pareto plot approximation which represents trade-off between the two criteria: maximize F1 and minimize F2. Red points are optimal solutions (set of non-dominated solutions) and blue points are realizable solutions (set of dominated solutions).

5. Conclusion

Railway traffic rescheduling in case of electric power shortage is an important process for proper operation of the railway network. In this document, we presented our rescheduling approach, based on regional sensitivity analysis. This type of sensitivity analysis is suited to our problem, since we are interested in finding which variables (adjustment actions) are important in order to respect the operational constraints and have an acceptable performance output. We applied this approach to multi-line test case, with heterogeneous traffic and we displayed some results. Based on our methodology, the operator can choose a final solution according to his priorities.

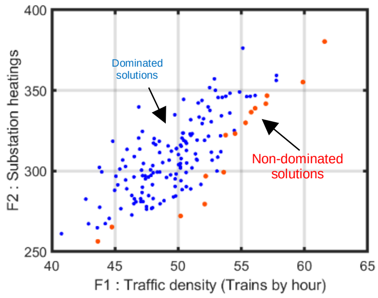

Fig. 5: Approximate Set of Pareto-optimal solutions

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