SELECTED PROCEEDINGS

EVALUATION AND COMPARATIVE ANALYSIS OF RAILWAY PERTURBATION MANAGEMENT METHODS

TORMO, JULIA, ECOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE, LITEP, CH-1015 LAUSANNE, SWITZERLAND JULIA.TORMO@EPFL.CH

PANOU KONSTANTINOS, UNIVERSITY OF AEGEAN, DEPARTMENT OF SHIPPING, TRADE AND TRANSPORT, CHIOS, 82100, GREECE PANOU@AEGEAN.GR

TZIEROPOULOS, PANOS, ECOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE, LITEP, CH-1015 LAUSANNE, SWITZERLAND P.TZIEROPOULOS@EPFL.CH

This is an abridged version of the paper presented at the conference. The full version is being submitted elsewhere. Details on the full paper can be obtained from the author.

ISBN: 978-85-285-0232-9

13th World Conference on Transport Research

www.wctr2013rio.com

15-18 JULY 2013 Rio de Janeiro, Brazil

EVALUATION AND COMPARATIVE ANALYSIS OF RAILWAY PERTURBATION MANAGEMENT METHODS

TORMO, Julia, Ecole Polytechnique Fédérale de Lausanne, LITEP, CH-1015 Lausanne, Switzerland julia.tormo@epfl.ch

PANOU Konstantinos, University of Aegean, Department of Shipping, Trade and Transport, Chios, 82100, Greece panou@aegean.gr

TZIEROPOULOS, Panos, Ecole Polytechnique Fédérale de Lausanne, LITEP, CH-1015 Lausanne, Switzerland p.tzieropoulos@epfl.ch

ABSTRACT

Real-time rescheduling is a dynamic process aiming to detect and solve conflicts that arise in everyday railway operations. The objective of this paper is to analyse and evaluate existing Perturbation Management Methods (PMM), in order to support the railway decision-maker in assessing the appropriateness of each method for the different fields of railway operations.
To evaluate the PMMs, an inventory is made based on a wide range of sources, such as scientific literature, EU projects, professional experience and databases. Moreover, a survey is conducted and the largest European Infrastructure Managers (IMs) are interviewed. The collected information is then systematically assessed against criteria such as: simplicity of method, performance and robustness, transparency, plugability and control, scalability and accountability.
Based on the above structure, the advantages and disadvantages of each PMM are assessed. The results show that there exist three main approaches to perturbation management; (a) the holistic, which aims to minimize overall delays at the network level; (b) the weighted, that assesses perturbation incidents according to the severity of their impacts; and (c) the disaggregate, assuming equal importance of each incident. All methods are critically reviewed with respect to their technical, usage and management characteristics. Possible gaps and/or room for improvement are also identified, including: innovative method architectures, real-time capability, user-friendly interfaces, extensibility, etc.

Keywords: Perturbation Management, heuristics, deterministic algorithms, knowledge-based, simulation, simplicity, performance, robustness, transparency, accountability, plugability, control, scalability.

INTRODUCTION

Perturbation Management (PM) deals with the treatment of real-time small-scale operational disturbances. Its purpose is to minimize the consequences of the knock-on delays produced by a perturbed train [Jacobs, 2008]. PM must result in efficient solutions within minutes, to be able to respond to the ever-changing state of the railway traffic in real-time.

The purpose of Perturbation Management (PM) is to minimize the consequences of delays in a railway network. Multiple approaches to tackle this problem have been developed during the last decades. There is a close relation between traffic density and perturbations in the railway network. In rush hours, when the small disturbance of one train may cause delays all around the network, the treatment of these disturbances to reduce the consequences on the network becomes a time-consuming and difficult issue. The train dispatchers, who are used to do this task manually, can find themselves overloaded in large and congested networks, and they might benefit from the help of automated conflict detection and resolution.

The main mathematical problem corresponding to perturbation management is (re)scheduling. It consists of "identifying and resolving conflicts which may arise during actual operations" [Jacobs, 2008].

The objective of this paper is to analyze and evaluate existing Perturbation Management Methods (PMM), in order to support the railway decision-maker in assessing the appropriateness of each method for the different fields of railway operations. It provides different evaluations and inventories of such methods, with the purpose of supporting railway decision-makers in assessing the appropriateness of each method for the different fields of railway operations.

The paper is structured in the following way: Section 2 presents the key concepts in PM, necessary to understand the context of the study; Section 3 assesses the most important PM methods in a two-phase approach; Section 4 presents the results and findings of the assessment and gives further recommendation on the methods; finally, Section 5 presents the conclusions of the study.

This paper builds on the research project ON-TIME "Optimal Networks for Train Integration Management across Europe" and more particularly on the research for perturbation management. The objective of this research is to increase railway capacity by reducing delays and improving traffic fluidity. The research has been taken with support from a stakeholder group representing European IMs, DBNetz, Prorail, RFF-DCF, RFI, Trafikverket and Network rail.

KEY CONCEPTS IN PERTURBATION MANAGEMENT

The PM problem consists in identifying the minimum cost feasible routing and scheduling of trains, in a given control area and in a predetermined time horizon. Routing and scheduling of trains is feasible as far as safety constraints are met and trains are not scheduled before their foreseen arrival in the control area, or their departure according to the timetable in case they originate at a station included in the control area itself. The cost of a feasible routing and scheduling is typically a measure of the delay assigned to trains in the area of reference. It can be measured in terms of, for example, journey time, connectivity, punctuality, resilience, energy, resource usage. These are also properties that characterize a good quality solution. Having delineated PM quality, its objectives and priorities can then be defined accordingly.

Numerous quality measures or indicators have been developed in the literature. Our approach builds on basic performance concepts, such as: quality of service, stability, robustness, reliability, punctuality, regularity, etc. to meet the PM requirements. This section presents the results of this process.

Quality of Service is an indication of the comprehensive performance of the railway system. This concept and the key performance indicators (KPI) that it includes, help set out the multi-objective decision making method. An objective function can eventually be developed for each KPI. As far as PM is concerned, there are 6 KPIs that could be taken into account in the determination of the Quality of Service:

1. Journey Time (JT): Minimize the difference of journey times relative to the scheduled sectional running times
2. Connectivity (CN): Minimize the difference of interchange times between selected services relative to the scheduled interchange times
3. Punctuality (PT): Minimize all train delays at selected stations
4. Resilience (RS): Minimize the delay propagation in the system
5. Energy (EG): Minimize the sum of energy consumed by trains
6. Resource Usage (RU): Minimize the track utilization percentage subject to the minimum traffic demand being met; minimize the rolling stock utilization percentage; minimize the crew utilization; minimize overall resource usage.

Thus, a possible objective function could be formed as follows:

$$O_{WP4} = f(JT, CN, PT, RS, EG, RU, W_n) \qquad (1)$$

where O_{WP4} is the objective and W_n is the weighting function for each KPI.

As mentioned, key concepts for state-of-art PM are the stability and robustness of the timetable. Stability is the ability to recover without active train rescheduling, and robustness is the ability to recover with active train rescheduling/ordering. Therefore, a more stable system will require less perturbation management, as it will be capable for absorbing more small perturbations by itself. A more robust system will apparently respond better to large-scale perturbation management actions.

The concept of reliability, which can be defined as “a measure of the likely performance of the timetable as a whole, in terms of schedule adherence”, is closely linked to Perturbation Management, since some of the factors that directly affect the timetable reliability are [Higgins et al., 1996]:

1. The degree of slackness of the schedule
2. The number and position of train conflicts
3. The priorities of each train
4. Terminal congestion
5. Number and nature of scheduled stops
6. Train speeds

Most of these factors are considered as variables in the PM problem, e.g. priorities of trains, speed, etc. The variation of these variables might lead to a good solution that minimizes delays, and therefore increases the reliability of the system.

Punctuality refers to the "percentage of trains that arrive at a location with a delay less than a certain time in minutes" [Hansen, 2008] It is considered of great importance for perturbation management as reduction of delays is one of its primary aims.

Regularity is also a crucial concept for perturbation management. Though some times related to reliability, it refers to the cancellation of trains which is often the only possible means to stop the propagation of delays. In principle, there are two kinds of delays: the primary delays, which are caused by disruptions within the process, and the secondary or knock-on delays, which are caused by conflicting train paths or waiting for delayed trains. When dealing with perturbation management, it is important to note that a delay (expressed in minutes) as the only magnitude, isn't enough to determine the severity of the situation: for example, sometimes it is more preferable to give priority to a 60 minute delayed train carrying few passengers, as opposed to 4 trains with 15 minute delay carrying a larger amount of connecting passengers.

Another noteworthy concept is recovery time, defined as the time between the delay of the system increasing above a small threshold, and it returning below this threshold. Here the definitions vary. In the UK for example recovery time refers to the time provided in the timetable for a train to travel from point a to point b over and above the time required for the train to travel between these points in non-perturbed conditions.

The above measures/indicators are intuitively linked with one-another, but they may imply different choices. For example, connectivity is strictly linked to punctuality, but it is possible that, when minimizing the latter, some connections might be lost so to allow a few more trains to arrive on time. Similarly, when maximizing connectivity, some trains might be delayed for avoiding missed connections. The problem becomes more pressing when a perturbation causing the emergence of conflicts occurs. Moreover, the problem is particularly relevant if the control area includes a junction, i.e., a piece of infrastructure where multiple lines cross. In fact, at junctions, trains can be delayed in suitable locations for changing their ordering (re-scheduling).

At junctions, several possibilities often exist for connecting origin-destination pairs, allowing the possible change of train routes for coping with traffic (re-routing). Even if safety issues do not emerge thanks to the signalling system that imposes the suitable headway distance between consecutive trains, often the use of the routes originally planned and the first-comefirst-served schedule, as is quite frequently done in reality, is not the most effective possibility. The solution of the PM problem allows the identification of the most convenient alternative, if it exists.

EVALUATION OF THE EXISTING METHODS

To evaluate the PMMs, the followed process comprised three steps:

1. Overview of existing methods: in order to acquire a global understanding of the perturbation management approach, a bibliographical research has been conducted, and a representative sample of methods has been withheld.

2. Shortlisting of methods: in order to focus on the most representative methods of the above, a pre-screening was carried out according to the rescheduling problem variant solved and the way that they are treating speed (i.e. fixed or variable speed).

3. Assessment of features methods: the selected methods are systematically assessed against a longer list of criteria such as simplicity, performance, robustness, transparency, accountability, plugability, control, and scalability.

Overview of existing methods

In the last decade, several variants of the PMM have been tackled, through both exact and heuristic algorithms.

The first paper devoted to the solution of the PM problem dates back to the 1970's: Szpigel (1973) proposed a branch-and-bound algorithm for tackling the PM problem as a scheduling problem. More recently, ASDIS, an asynchronous simulation method that adapts and adopts methods from the timetabling problem to real-time traffic management was developed in Jacobs (2004) and Jacobs (2008).

Various authors have described heuristic algorithms for solving the PM problem with no re-routing option [Lamma et al., 1997; Chiu et al., 2002; Dessouky et al., 2006; Chen et al., 2010]. These algorithms tackle fixed-speed models and are based on different problem solving techniques: Lamma et al. (1997) present a constraint logic programming, Chiu et al. (2002) and Dessouky et al. (2006) a branch-and-bound method, and Chen et al. (2010) a differential evolution method named JRM (Junction Rescheduling Model).

Ho and Yeung (2001) present a Deterministic Method solved with Heuristic Methods (DMHM) such as genetic algorithms, tabu search and simulated annealing that considers variable speeds. Ping et al (2001) present a Model for Train Dispatching using Heuristic Approaches (MTDHA) that uses fixed-speeds, similar to the Dispatching using Heuristic Algorithms (DGA) developed by Wegele and Schnieder (2005).

Fay (2000) and Fay and Schnieder (1997) present a fixed-speed expert system that uses Petri Nets and suggest a fuzzy rule-base for train traffic control during disturbances, referred to in this paper as KBFPN (Knowledge-Based Fuzzy Petri Nets method) while Tazoniero et al. (2005) describe another Knowledge-Based system with Ruled-Based Fuzzy Set techniques but that considers variable speeds (KBRBFS).

The research direction that has had the greatest follow-up is based on the alternative graph. First in this research stream, a fixed-speed algorithm for dealing with the PM problem with both fixed block and moving block signalling systems, was proposed in the context of the research project COMBINE [Mascis et al., 2002]. In the evolution of this project, namely in the project COMBINE2, an advanced Traffic Management System (TMS) based on another heuristic algorithm was proposed [Mazzarello and Ottaviani, 2006].

Almost concurrently, D'Ariano et al. (2006) have used a similar alternative graph formulation for modelling a simplified version of the PM problem, and have proposed a branch-and-bound fixed-speed algorithm for tackling this variant. D'Ariano and Albrecht (2010) combine this approach with a heuristic for computing suitable train speed profiles.

The no-re-routing variant of the problem has also been tackled by D'Ariano et al. (2007b) through a variable-speed heuristic algorithm: first a solution is found considering the fixed-speed branch-and-bound procedure; then a check is made for verifying the actual feasibility of the solution found considering speed variation dynamics.

D'Ariano et al. (2008) have hybridized the fixed-speed branch-and-bound algorithm by D'Ariano et al. (2006) with a tabu search approach. This two step approach is named ROMA (Railway traffic Optimization by Means of Alternative graphs).

Corman et al. (2009) have applied the branch-and-bound approach introduced by D'Ariano et al. (2006, 2007b) and two other existing heuristics for assessing the potential of the so-called green wave policy.

A completely different formulation has been proposed by Rodriguez (2007). He proposes a Method Solved with a Constraint Scheduling Formulation (MSCSF). It is exploited in both a fixed-speed and a variable-speed algorithm.

The difference between fixed and variable-speed algorithm is overcome by Caimi et al. (2011, 2012), who have considered a variant of the problem in which trains cannot be delayed within the control area under analysis.

Lusby et al. (2012) have presented a heuristic variable-speed algorithm based on a set packing formulation. For having the tractability of realistic size instances through this algorithm, the time horizon needs to be discretized.

For tackling instances representing very large control areas, Törnquist and Persson (2006) have proposed a mixed-integer linear programming formulation used for N-tracked networks (N-TOA). Yet, the model proposed is not usable due to the excessive computation time. Hence, the authors have proposed alternative strategies for obtaining tractable sub-instances through heuristics (N-THA) [Törnquist, 2012].

Shortlisting of existing methods

The rescheduling problem can be tackled in three different ways:

1. Mathematical optimization, which consists of maximizing or minimizing a real function by introducing the input values and computing the value of the function.

    a. Heuristics: Greedy Algorithm (GrA), Genetic Algorithm (GA), Evolutionary Algorithm (EA), Tabu Search (TS), Simulated Annealing (SA)
    b. Deterministic algorithms: by contrast with the above, they have no randomness, and therefore will give the same output with the same input every time.

2. Knowledge-Based, which uses logical or heuristic means to draw conclusions from a database that store and collate knowledge on specific problems and then uses [Jacobs, 2008].

3. Simulation

As concerns speed variability, Fixed-Speed models assume that trains follow a fixed speed profile. In fixed-speed algorithms, train speed variation dynamics are completely neglected: trains are supposed to accelerate and decelerate instantaneously and in no space. The feasibility of the different speed profiles is then checked for each train. Variable-Speed models, on the other hand, consider the state of the signalling system and other regulations when anomalies occur, and re-plan the train movements according to it.

Based on these definitions, the most representative methods for the different variants of the rescheduling problem have been identified and are presented in table I. It is noted from table I, as well as from the previous section that there is a clear trend towards the use of heuristic optimization techniques, which may or may not incorporate knowledge from human dispatchers, blending the knowledge-based approach and the mathematical optimization methods in one. In doing so, the algorithmic methods that are built to find the global optimum with respect to the goal function are relegated in favour of others that find good but not necessarily optimal solutions in short times, and are therefore applicable in real-time.

Assessment of featured methods

The purpose of this section is to assess the most featured methods of the rescheduling problem according to the following criteria:

1. Simplicity. The simplicity can be measured as "a method's ability to provide a crisp and well-defined methodological representation of complex real world decisions" [Tsamboulas et al., 1999]. The feature will be assessed subjectively, by trying to determine how intuitive the method is, and how easily understandable it is for a person with only basic knowledge in the field.

Table I – Classification of PMM according to the rescheduling method and the variability of speed

METHOD	**SPEED VARIABILITY**	**MATHEMATICAL OPTIMIZATION**						**KNOWLEDGE-BASED**	**SIMULATION**	**OTHERS**
		HEURISTICS					**DETERMINISTIC ALG.**			
		Gr. A	**GA**	**EA**	**TS**	**SA**	**BB**[1]			
ROMA	FS				*X*		*X*[2]			
	VS	Constructive heuristic algorithm for the dynamic modification of running times								
JRM				*X*						
MSCSF	FS						*X* (to solve CPM[3])			
	VS									
N-TOA	FS						*X* (to solve MILP[4])			
N-THA	FS	*X*								
TMS	FS	*X* (AMCC)								
	VS									*X* (CDP[5] techniques)
MTDHA	FS		*X*							
DMHM	VS		*X*		*X*	*X*				
KBFPN	FS							*X*		
DGA	FS		*X*							
KBRBFS	VS							*X*		
ASDIS	FS								*X* (Asynchronous)	

[1] Branch and Bound
[2] Upper bound is the best value of FIFO/FOFI/AMCC
[3] Constraint Programming Method
[4] Mixed-Integer Linear Programming
[5] Constraint Dynamic Programming

2. Performance and robustness:

    a. Performance. The performance is a measure of the quality of the solutions, normally measured in computation time and in optimality of the output.

    b. Robustness refers to "the operational efficiency of a method". It is assessed in terms of data requirements, treatment of any number or type of disturbances, treatment of uncertainty (i.e. if it can deal with probabilistic distributions of certain data), and sensitivity (the ability to handle the differences that may result when changing criteria or other attributes).

3. Transparency and accountability. This feature deals with how traceable the method is [Tsamboulas, 1999]. More specifically, the methods were assessed according to:

    a. How well structured and easy to follow they are
    b. How well they cope with real world situations

4. Plugability and control[6]. This feature is related to the ability of the software to receive information from other software or to feed information to them.

5. Scalability. The scalability deals with how capable the software is of adjusting to different scales, like passing from line to network. It can also refer to is capability to adjust to longer time horizons.

One or more representative methods have been selected of each category (i.e. two deterministic methods, three heuristic methods, one knowledge-based method and one simulation-based method) and were tested against the criteria presented above.

Method 1. ROMA

The ROMA (Railway traffic Optimization by Means of Alternative graphs) method uses an optimization algorithm for the real-time management of a complex rail network and a constructive heuristic algorithm for the dynamic modification of running times (to assure the feasibility of the running profile, while respecting the signalling and train protection systems).

Performance and Robustness. Four performance studies have been made [D'Ariano et al., 2006], the results of which are here summarized:

1. BB with/without AMCC as initial solution, with 1 or 2 h of time horizon: AMCC reduces computation time in about 50%, and reduces the number of iterations.

2. BB compared to FIFO/FOFI/AMCC:

[6] This criterion, as well as the next (Scalability) refer to possible software implementations. When no software has been developed or is not known of, they won't be considered.

a. In terms of goodness of solutions, it reduces the maximum consecutive delay in more than 100 sec with respect to FIFO/FOFI and the average consecutive delay in more than 50%. In relation to AMCC, it finds similar results.
b. The average computation time is less than 2 sec.
c. It finds an optimal solution in 297/300 cases in less than 120 sec.

3. Effects of static implications[7]: BB finds the optimal solution in 100% of the cases with static implications, while only in 50% without.

4. Analysis of "hard instances" (the most critical in terms of computation time): Enlarging the computation time to 7200 sec, the method was able to find the optimal solution for most cases.

In terms of robustness the method shows the following features:

1. Data requirements: It uses quite detailed off-line input data including infrastructure data (stations, signals, switches, speed limits, track layouts, signalling rules), rolling stock data (train length, standard acceleration & braking tables, initial speeds & positions) and timetable data (scheduled arrival/departure times, scheduled paths, stochastic disturbances), thus allowing for the calculation of more stable and robust to small perturbation, new target timings.

2. Treatment of any number or type of disturbances: the method has been tested (and proved successful) with a number of disturbed trains varying from 7 to 27 (out of 54 circulating trains), and the value of the delay is generated based on Gaussian and uniform distributions (in the time window of typical train delays). It is interesting to note that the method is more time consuming in terms of level of disturbance than in terms of time horizon (see Scalability). The method is reported to perform well with a percentage of perturbed trains that goes up to 50%, but this percentage may be limited due to the fact that the level of disturbance is consuming in terms of computation time.

3. Treatment of uncertainty: as has been explained before, the uncertainty is introduced through stochastic values of delays. The method works with deterministic speeds, although different driver behaviours can be implemented [D'Ariano, 2008]. This allows the method to adapt to reality, since, as stated in the OPTIRAILS project[8], "truly fixed paths do not likely exist, as in fact they only nominally follow the scheduled timetable, with random (even minor) variations." Therefore, it could be questionable to counteract a naturally "stochastic" system by trying to make it even more "deterministic".

4. Sensitivity: it is not clear how the method performs in terms of sensitivity, as no relevant information was available. However, it is interesting to note that the method

[7] Static implications are those that can be computed off-line, based on the track topology of the network.
[8] European research project aiming at specifying a rail traffic management system architecture applicable to the international railway corridors, with the purpose, among others, of improving real-time train dispatching and fluidity.

can deal with aspects of perturbation resolution to meet the standards of the different stakeholders; for example, by introducing dynamic priorities of trains and by changing the objective function.

Transparency and Accountability. The method is based on the Alternative Graph Formulation. This means that the mathematical problem, as well as the constraints, etc. are well documented and accessible. So are the algorithms used. There are pseudo-codes and comments to support the method traceability. All of these features make the method easy to track and to understand (however, according to the developers of the method, improvements in its traceability could be made). No real-world tests have been made, and therefore no assessment of this feature can be done.

Plugability and Control. At this point, the ROMA tool doesn't have any specific interfaces to external applications. However, a conversion tool can be developed to import various micro simulation tool results, for example FRISO[9].

Scalability. Geographically, the software can be used in small areas or in larger networks, with the help of a coordination system which solves the problem locally and coordinates the solutions in contact points through congruence equations [Corman et al., 2012]. Tests have been done with one and two hour time horizons, without any significant changes in the quality of the results. It uses standard formats (XML format or text files) for infra/train models, which makes it reusable for any kind of situation.

Method 2. JRM

The Junction Rescheduling Model (JRM) focuses on the retiming and re-sequencing of perturbed train services approaching junction points or 'bottleneck portals'. For the solution of the problem, an improved differential evolution algorithm (DE-JRM) has been developed. Two procedures may be used to produce a feasible timetable: re-sequencing and retiming.

Performance and Robustness. The performance has been statistically evaluated with the Monte-Carlo Methodology. The results, found in Chen et al. (2010), are the following :

1. Average computation time: 2-3 sec
2. Reduced SWAD (Statistical Weighted Average Delay) compared to FCFS and ARS[10] (the SWAD is reduced of more than 50% on most cases with respect to FCFS).

The delay is reduced greatly in comparison to techniques that are frequently used by dispatchers in the area. Furthermore, the computation time is kept short, allowing for the method to adapt to real-time applications.

In terms of robustness the method shows the following features [Chen, 2012]:

[9] Dutch microscopic simulation tool developed by ProRail
[10] Conventional Automatic Route Setting

1. Data requirements: The model is in general macroscopic; however, the running times are obtained using a microscopic simulation, with data such as line speed limits, train mass, maximum power, static friction coefficient, parameters for the Davis train resistance equation, service braking deceleration rate, etc., thus allowing detailed single-train and multi-train simulators to calculate the precise section running time.

2. Treatment of any number or type of disturbances: The different types of disturbances tested correspond to the following statistical distributions:
   a. Empirical distribution over [-300, 480] based on existing operational train delay data
   b. Normal distribution over [-30, 120] for short train delays
   c. Normal distribution over [-60, 300] for long train delays
   d. Negative exponential distribution over [0, 480]

   This proves that the method has been tested for both short delays and long delays, even though there is no knowledge of the exact number of disturbances tested.

3. Treatment of uncertainty: The uncertainty is introduced through stochastic values of delays, as can be seen above. Like for the ROMA method, this allows for a better representation of reality and to check whether the algorithm can handle different delay scenarios in case of a perturbation or disturbance.

4. Sensitivity: It is not clear how the method performs in terms of sensitivity as no relevant data was available. Nonetheless, it has been reported that the method is tested for short and long delays, and in both cases good results were produced.

Transparency and Accountability. The method is only partly formal, in the sense that the algorithm isn’t completely and precisely defined mathematically. It is well structured and apparently easy to follow. Its traceability is supported by, for example, the existence of a pseudo-code. No real-world applications have been done so far.

Plugability and Control. To this day, there is no share of information with other software. However, Chen (2012) proposed an integrated system architecture of traffic management and train control to implement the methodology in real world situations, by receiving dynamic information from the operation, real time train location, etc. and giving instructions to drivers.

Scalability. The method is applied to bottlenecks and junctions. It has been constructed for 10 km of line, 2 junctions and about 24 trains/hour, and its possible expandability hasn’t been studied yet. However, authors report that the DE_JRM is easy to extend as all parameters are configurable and the algorithm has been packaged into specific modules.

Method 3. MSCSF

The MSCSF method uses a constraint-based scheduling formulation of the train routing and scheduling problem. The method can solve scheduling, routing, or combined scheduling-routing problems. The input comes from relevant time events of trains calculated with the help of the OpenTrack simulator[11].

Performance and Robustness. To assess the performance of the method, a real case study was proposed by the French operator SNCF [Rodríguez, 2007]. 10 instances were studied, created by adding conflict trains and therefore increasing the difficulty. The first model, which considers the acceleration phase, had a computation time ranging from 9 to 110 sec. The model that doesn't consider the acceleration phase was less time consuming, less than 7 sec. The reduction of the delays for both models was between 62 and 95% (with respect to the "Reference" state calculated with the SYSIFE simulator that simulates the decisions taken by the operator). However, the second model, without the acceleration phase, gave slightly lower quality solutions in some instances.

In terms of robustness the method shows the following features [Rodríguez, 2007]:

1. Data requirements: The model is based on track circuit occupation times, signalling aspects, interlocking constraints, train entrance times, train exit orders and planned routes, thus allowing for the consideration of the entire capacity that can actually be exploited, which is artificially limited when decisions concerning sequences of track portions are combined for reducing the size of the problem instance.

2. Treatment of any number or type of disturbances: The problems studied treat a number of trains ranging between 6 and 24, with a number of disturbances that increases proportionally to the number of trains. These conflicts include merging routes, crossing routes, opposing routes, and a mutual route of two trains with different speeds. In summary, the method was tested under varying number of disturbances, and proved robust enough. It is noteworthy that the typical conflicts presented in the network were also effectively treated at the same time.

3. Treatment of uncertainty: There is no stochasticity in the tests that have been carried out, which limits the method's representation of real world situations.

4. Sensitivity: It is not clear how the method performs in terms of sensitivity as no relevant data was available. However, there is a degree of freedom in user intervention by adding constraints or changing the criteria used in the resolution method.

Transparency and Accountability. It is well structured and apparently easy to follow. Its traceability is supported by, for example, the existence of a pseudo-code. No real-world applications have been done so far.

Plugability and Control. There is no share of information with other software, and there are no interfaces to external applications.

[11] OpenTrack is an object-oriented modelling simulation in railways, developed at the Swiss Federal Institute of Technology.

Scalability. The method is applied to bottlenecks and junctions. It has been calibrated for the Utrecht Den Bosch line (about 50 km of line, and 5 or 6 big stations). At present, they are treating a complete day (over 100 trains). The scalability of the software will depend on factors such as the number and type of constraints, the computation time, etc., which are regulated by the infrastructure managers.

Method 4. N-THA

The method presented in Törnquist Krasemann (2012) is an optimisation approach to the problem of re-scheduling traffic in an n-tracked network, based on a heuristic approach that produces optimal or near-optimal solutions, to solve the issue of problem size and intractability frequently found when using standard optimisation software.

Performance and Robustness. The performance of the method was evaluated against the solutions of the CPLEX[12] solver version 10. In terms of computation time, it took the method less than 1 second to find a first solution, and other solutions were found in the first few seconds. In general, the algorithm behaves well (the average difference of the sum of final delays with respect to the solver that obtains the optimum solution is of 2 minutes). It has been observed however that for the third type of perturbation (see below), there were difficulties in finding good enough solutions. These results show that the method is adaptable to real-time environments, and that near-optimal solutions can be obtained.

In terms of robustness the method shows the following features:

1. Data requirements: The level of detail is quite macroscopic, since the network is divided into sections, and the blocks that form the sections aren't explicitly modelled, but trains can run in the same direction when separated by sufficient headway. This is probably a necessity in the trade-off between accuracy and performance, in order to assure the real-time applicability.

2. Treatment of any number or type of disturbances: Even though there is strictly no variation in the number of disturbances, the method treats three kinds of perturbations:
    a. Train entering with a certain delay (between 6 and 12 minutes)
    b. Train with a malfunction resulting in increased running times
    c. Infrastructure failure perturbing all the trains passing through it

    This is a very innovative way of treating disturbances, different to what is found in most methods, and a better reflection of what happens in reality.

3. Treatment of uncertainty: It is not clear how the method treats uncertainty.

4. Sensitivity: It is not clear how the method performs in terms of sensitivity as no relevant data was available. The different kinds of perturbations treated demonstrate that the method isn't very well adapted to the third.

---

[12] Optimization software package

Transparency and Accountability. The method is apparently very transparent, with even outlines of the Greedy algorithm used. No applications in real-world exist so far.

Plugability and Control. There is no specific reference to the possible plugability and control of its software. The study of the method doesn't suggest any exchange of information with other software.

Scalability. A test was performed in a sub-network in Sweden (28 stations, 32 double and single-tracked sections). There is no specific reference to the possible scalability of its software.

Method 5. TMS

Mazzarello and Ottaviani (2006) presents an advanced Traffic Management System (TMS) that takes into account detailed information such as actual position and speed of each train, dynamic characteristics of the train, actual status of the infrastructure, characteristics of the infrastructure such as gradients, admissible speeds, signal positions, etc. to optimise traffic fluency in large railway networks equipped with either fixed or moving block signalling systems.

Performance and Robustness. 2 tests have been performed.

1. The first (not tested in real railway environment) is based on the Schiphol bottleneck, of approximately 44 km of line. The result is that the average throughput time is reduced with respect to reference values calculated with the approaches of local regulators (about 20% reduction). No specific results on computation time are given, although it is said to be fast enough.

2. The second is a real-world test (The Green Wave) in a bottleneck area with about 55 km of lines. With three delayed trains (with delays of between 1 and 5 min each), the method was capable of reducing the exit delay in about 60%. On weekdays, the method achieved gains of about 210 min for the whole area, and energy saving of about 10%. The computation time was estimated in a few seconds.

While the first test obtained good solutions (but not as good as some of the methods previously studied), the second test reduced greatly the exit delays, while maintaining the computation time in a few seconds.

In terms of robustness the method shows the following features:

1. Data requirements: Data requirements include the position and speed of each train, the technical characteristics of the trains (traction, weight, length, etc.), and the infrastructure characteristics (gradients, admissible speeds, signal positions and signal patterns). Besides this very detailed static data, on-line data is also handled, like sudden infrastructure or train degradations or process plan changes during a session, through interfaces with the real world, allowing for a very close representation of the real world.

2. Treatment of any number or type of disturbances: For the first experiment, although no specific information about the number of disturbances is given, the number of trains per hour tested is greatly varied (19 to 32 trains/hour), and two kinds of perturbations are treated (entry delays and stop extensions). For the real-world test, only data for one case (3 delayed trains) is given, although the test took place on 8 days, which means that necessarily the number of disturbances varied greatly. There is not enough information to assess the differences in the disturbances treated.

3. Treatment of uncertainty: Uncertainty can be introduced through stochastic distributions of the delays (like in the first experiment).

4. Sensitivity: It is not clear how the method performs in terms of sensitivity as no relevant data was available. However, the method has proved to function relatively well both on-line and off-line, with fixed and moving block signalling systems.

Transparency and Accountability. The method maturity suggests that it is formal, and all the steps of the process are based on mathematical unambiguous and logical definitions. It deals apparently well with real-time situations, although only one experiment has been made so far.

Plugability and Control. The method has been tested in real world situations. To do so, it has been connected to external modules (in particular, with the Tracking and Tracing System (T&T) and the Procesleiding system (VPT-PRL). Plugability with other systems hasn't been reported. Furthermore, studies for the use of abstract interfaces and standard data formats for a more efficient exchange of information among applications are being conducted. The aim is to make it more independent of the chosen implementation.

Scalability. The software, thanks to its layered system architecture, is suitable for networks of any size through the decomposition of large network in local areas. Besides, its modularity allows it to manage different signalling systems (such as fixed and moving block).

Method 6. KBFPN

Fay (2000) and Fay and Schnieder (1997) present a method that uses a Fuzzy Petri Net notion to model a rule-based expert knowledge that uses fuzzy rules of the IF-THEN in a decision support system. The dispatching support system contains a knowledge-based decision support system, a simulation tool and a graphical user interface.

Performance and Robustness. One prototype has been developed for this method; instead of implementing the whole dispatching system, the key components (human-computer interface, simulation, and decision support system) have been implemented. No detailed information on the trials of this prototype has been found.

In terms of robustness the method shows the following features:

1. Data requirements: The simulation component can easily be adapted to the traffic system being examined, and the level of detail can be adjusted accordingly. The

simulation input consists of information on the traffic network, the train characteristics, and the schedule. Being a knowledge-based model, it also requires a collection of expert knowledge, presented as rules-of-thumb, to guide the dispatching process.

2. Treatment of any number or type of disturbances: It is not clear how the method performs when faced with different number or type of disturbances as no relevant data was available.

3. Treatment of uncertainty: To treat the vagueness that characterizes knowledge-based methods, two fuzzy concepts are used (use of fuzzy numbers to represent the “truth” of a condition, and “credibility factors” attached to every rule).

4. Sensitivity: It is not clear how the method performs in terms of sensitivity as no relevant data was available.

No definite conclusions can be drawn from the performance and robustness tests, because no results have been publicly reported.

Transparency and Accountability. Generally, in knowledge systems, it is hard but also crucial to draw a connection between aims and rules to establish the traceability between thoughts. In this case, our impression is that the system isn’t very transparent. It isn’t possible to access the exact rules that form the knowledge base, and therefore there is no way to understand how the decisions are taken (this, however, doesn’t mean that there doesn’t exist a clear connection, but known mainly by the developers or by the users; in fact, dispatchers are presented not only with the best conflict solutions, but also with explanations of how they were found). No applications in real-world exist so far.

Plugability and Control. With the results of only one prototype implementation (which didn’t even cover the whole dispatching system), there is no way to have practical results of its plugability and control. However, the literature affirms that having a flexible and modular structure, the software can be integrated in a control centre. Besides, the simulation input and output is provided in text files, which allows for the system to be easily parametrized for any traffic system, and it can be used as a dispatching support system for different public transport systems.

Scalability. Like for the previous criteria, the only prototype implementation doesn’t allow to extract conclusions about this feature. The only reported feature is that the knowledge base is stored separately from the inference machine (inversely to what happens in conventional algorithmic programming) to ensure maintainability and adaptability.

Method 7. ASDIS

In Jacobs [2004], the author presents a method based on an asynchronous simulation to generate new, conflict-free schedules. It consists on using an exact computation of the running times that provides the determination of the blocking times for the conflict detection[13]. ASDIS was integrated in the DisKon project [Kuckelberg and Wendler, 2008].

Performance and Robustness. A prototype of the method has been developed in the laboratory. No data has been found to evaluate the method's performance and robustness.

Transparency and Accountability. The authors' experience is that the method isn't very transparent for third people, since the information found includes no detailed information of the exact functioning of the method, algorithms, objective functions, etc.

Plugability and Control. No tests have been done in real world, but the developer affirms that it is capable of being used at traffic control centres. Besides, since all trains of a same priority category are inserted at the same time at not following a specific order, it is universally applicable for sections of networks.

Scalability. No tests have been done, but the developer affirms that being as it is an asynchronous simulator, it is capable of dealing with conflicts far away in the future, which contributes to its easy application to wide-area traffic regions.

RESULTS/ FINDINGS

Based on the above analysis, the advantages and disadvantages of the revised PM methods are assessed in more detail. Table II provides the scores that the methods received against the used criteria in a scale of 1 to 3, with +++ being the best score. The criteria that are not applicable for a method (or there was not enough information) are graded with 0.

To provide a better overview of the methods, they were categorized according to how they treat delays in a network level. More specifically:

1. Holistic: these methods aim at minimizing the overall delays at the network level, and are not concerned for local repercussions or discrepancies. It is therefore aspatial.
2. Weighted: the methods assess the perturbation incidents according to the severity of their impacts and promotes the most critical for immediate resolution.
3. Egalitarian or disaggregate: these methods assume equal importance of each incident and considers the location and speed of each train at a disaggregate level.

It can be seen from table II that the methods perform differently against the considered criteria: they're all reported to perform well in terms of computation time and goodness of results (with the exception of the third type of disturbance for N-THA); off-line data allows to establish different levels of detail, ranging from the most macroscopic methods (like N-THA) to the more microscopic ones, like TMS, passing through the mesoscopic models, like JRM.

[13] The prototype showed that the method offers a good dispatching assistance both under laboratory conditions, and within the control centres of the DB NETZ AG.

Table II – Advantages and disadvantages of the selected PMM

			ROMA	JRM	MSCSF	N-THA	TMS	KBFPN	ASDIS
MAIN APPROACH			Disaggregate	Weighted	Holistic	Weighted	Disaggregate	Holistic	Weighted
SIMPLICITY			+++	++	+++	++	+++	+	0
PERFORMANCE	TEST QUALITY		+++	+++	+	++	+++	+	0
	COMP. TIME		+++ [14]					0	
	GOODNESS RESULTS[15]		+++	+++	+++	++	+++	0	0
ROBUSTNESS	DATA[16]	OFF-LINE	++	++	+++	+	+++	++	+++
		ON-LINE	0	0	0	0	+++	0	0
	#/TYPE DISTURB.		+++	+	++	++	++	0	0
	UNCERTAINTY[17]		++	+	0	0	+	([18])	0
	SENSITIVITY		0	0	0	0	0	0	0
TRANSPARENCY, ACCOUNTABILITY[19]	STRUCTURED		+++	++	++	++	+++	+	+
	REAL WORLD		0	0	0	0	++	0	0
PLUGABILITY, CONTROL			+	+	0	0	++	+	+
SCALABILITY	GEOGRAPHICAL		+++	0	++	0	+++	+	+
	TIME HORIZON		++	0	0	0	0	0	0

[14] Considering a computation time limit of 180 sec, which is the limit considered reasonable for real-time operations according to SNCF (c.f. [Rodríguez, 2007]), all methods have very good computation times.

[15] No specific scale can be given for this criteria, since some methods compare the results with the FCFS strategy (ROMA, JRM), others with the solution found when simulating the decisions taken by the operator (MSCSF, TMS), and others with respect to the optimal solution (N-THA). However, for one reason or another, all of them prove to have good results in most cases.

[16] In general, microscopic data are scored with +++, while macroscopic data are scored with +. Anything in between would be given ++.

[17] Uncertainty can be introduced through different means, like stochastic delays, running times, different driver behaviours, etc. If one issue treats with uncertainty, it will be given a +, two will be given ++, etc.

[18] This doesn't apply to the uncertainty that relies in the construction of knowledge-based systems.

[19] No knowledge of the existence of pseudo-codes or comments to help achieve the traceability of the method (for N-THA, TMS and KBFPN). The grades have been given according to the authors' intuition when reading the articles available on these methods.

The only method that incorporates on-line data, since it has been tested in real-time, is TMS. Most of the methods combine the variability in the number and type of disturbances and the uncertainty, in order to elaborate a wider range of experiments. In this area, N-THA merits to be highlighted, since it doesn't only treat entrance delays, like most methods, but incorporates train malfunctioning and infrastructure failures to model other kinds of perturbations. Another interesting characteristic is the ability of ROMA to model different driver behaviours, thus allowing to introduce certain variability in the running times.

Of all the methods studied, only TMS has been tested in real railway operating environment. Most of the other methods, however, make reference to their ability to receive and feed information to other software, and, consequently, to their capability of being incorporated to traffic control centres to manage real railway operating situations. It is interesting to highlight the reported ability of KBFPN to be used as a dispatching support system for different public transport systems.

Once again, the scalability of the method varied greatly. TMS reported that its layered system architecture allows for the decomposition of large networks into local areas (similar approach to the one followed by ROMA), while JRM is limited to junctions and bottlenecks and the possible scalability hasn't yet been studied. ROMA is the only method to report having successfully tested the method for two different time horizons.

Following that assessment, table III presents the innovative features, user-friendliness, extensibility and the more important usage and management properties of the methods. They are classified in the following fashion: positive features, features to improve, and recommended work for the future.

It can be noted from Table III that most of the methods' future developments, let alone concrete mathematical improvements of the algorithms, include integration into traffic control centres in order to manage trains dynamically. This is a consequence of the fact that most of the methods have not yet been applied in the 'real world' of railway operations so some integration is needed. The latter emphasizes the importance of enhancing plugability and control, as well as the methods' scalability and their ability to be less dependent of the specific implementation and more focused on core functionalities. Some methods have, for now, very limited scope, being only focused on junctions or not considering freight trains, and still need improvement on these areas. Another interesting aspect is that, more and more, the methods make use of variable speeds to ensure a more effective reflection of real world situations, and that some functioning on more user-friendly means to facilitate the dispatchers' duties.

Table III – Additional advantages and disadvantages not discussed previously

METHOD	POSITIVE FEATURES	POSSIBLE LIMITATIONS OR IMPROVEMENTS	FUTURE WORK
ROMA [D'Ariano, 2008], [D'Ariano et al., 2006], [Corman et al., 2012]	2 complementary modules: a CDR (Conflict Detection and Resolution) module based on fixed speeds, and a train speed coordination process.	▪ No concurrent processing/communication. ▪ Simplifications: driver behaviour assumed known in advance (standard braking and acceleration profiles); weather condition, train load (number of passengers) and weight assumed to be a priori defined.[20] ▪ Modifications or the addition of further functions requires the modification of the source code.	▪ Connect ROMA to a closed-loop traffic monitoring and control system and receive real-time data to be able to manage trains dynamically. ▪ Illustrate automatically and present the dispatching measures through user-friendly means, to make the dispatchers' work less complex. ▪ Include a decision support system for drivers to enable a more efficient regulation of the train speed profiles.
JRM [Chen, 2012], [Chen et al., 2010]		▪ Focused on junctions or bottlenecks. ▪ Freight trains not considered. ▪ No concurrent components (parallel event streams can't be handled efficiently).	▪ Combined with HERMES[21], it could be adopted in larger networks.
MSCSF [Rodríguez, 2007]	2 complementary modules: ▪ a simulation module for the train and driver behaviour, and a constraint programming (CP) model for the signalling system behaviour. ▪ The CP model can be with or without "acceleration time" (wasted time during the acceleration phase).	▪ Focused on junctions. ▪ Currently, there is no concurrent processing/communicating.	▪ Integrate the two CP models in one (depending on the situation, one or the other prove better). ▪ Consider pre-processing to be able to reduce the size of the instances and improve performance.
N-THA [Törnquist Krasemann, 2012]	3 distinct categories of perturbations (see above), even though the algorithm isn't very successful for the third.	▪ Limited ability of the algorithm to handle deadlocks at stations where a line splits up. ▪ The algorithm is rather conservative after finding the first solution, and it prefers to avoid a deadlock than to find better solutions.	▪ Work on the implementation of multi-threading, which would allow parallel computing. ▪ Work on the development of a more detailed modelling. ▪ Work on more effective selection of potential branching nodes.

[20] Obviously, these simplifications, as well as many others presented here, are explained by the trade-off between accuracy and computation time required in all real-time implementations, and therefore they are not only admissible, but necessary.
[21] HIT Rail's Hermes VPN is a reliable, powerful and secure communication platform used for the transmission of data between European railway companies.

METHOD	POSITIVE FEATURES	POSSIBLE LIMITATIONS OR IMPROVEMENTS	FUTURE WORK
		▪ Apparent difficulty to treat the third category of perturbation.	▪ Work on giving the initial solution provided by the heuristic as a start solution for CPLEX22.
TMS [Mazzarello and Ottaviani, 2006]	2 core modules: ▪ CDR (Conflict Detection and Resolution): can work as stand-alone tool or with SPG and other communication tools. ▪ SPG (Speed Profile Generator): makes it possible to handle real-time flexible traffic.		Use of abstract interfaces and standard data formats to ensure a more efficient exchange of data between the applications, and therefore to make TMS less dependent of the implementation and more focused on the core functionalities.
KBFPN [Fay, 2000], [Fay and Schnieder, 1997]	Design of a prototype of human-computer interface, based on the tasks of the dispatcher. The conception of the interface increases the dispatchers' working quality and satisfaction. To reduce the amount of data, the information is classified according to the importance to the dispatcher.	Offers two alternative approaches for the construction of the simulation tool: a simulation based on Petri Nets and an Object-Oriented simulation. However, the Petri Net simulation still suffers from deficiencies in the commercial Petri Net tools available.	The next step to commercializing the application will be its integration into a concrete train traffic control system.
ASDIS [Jacobs, 2004], [Jacobs, 2008]	▪ Asynchronous algorithms are very appropriate to eliminate conflicts in network with very diverse types of trains. ▪ ASDIS upgrades older asynchronous algorithms and, under certain circumstances, has access to synchronous elements. ▪ The traffic controller receives the rescheduling measures obtained by the method; he can change or intervene by, for example, changing priorities of trains.	In general terms, asynchronous models have a limited capacity to integrate with connectional and circulation conflict management, reason for which the trend goes towards increasing synchronous elements in asynchronous models.	Make ASDIS capable to make decisions internally in certain standard situations (advance towards automated data processing)

[22] Optimization software package

CONCLUSIONS

It has been shown that there is a high degree of specificity with regards to methods that solve the problem of perturbation management. This includes different objective functions, problem variants, levels of detail, geographical areas, etc. collide and result in very different approaches to tackle the problem.

This study has focused on highlighting the differences, but also the most recurrent aspects, in perturbation management methods, in order to guide the reader towards possible lines of action in the different fields of railway operations. While some methods stand out for their management properties, others may be pioneers in treating real-time data, or may work with extremely detailed input data while keeping short computation times. This paper underlines these differences in order to help train operators improve their real-time traffic management and therefore achieve a faster recovery from incidences, enabling a more efficient use of energy and capacity, a higher punctuality and the consequent increased user satisfaction.

The work presented above contributes to research in the field of railway automation and control. It provides the necessary background knowledge to railway stakeholders aiming to introduce more automation to their existing perturbation management systems. As a result, recovery or reduction of the consequences from incidents or disturbances becomes faster, enabling more efficient use of capacity, higher punctuality and increased user satisfaction.

REFERENCES

Caimi, G., F. Chudak, M. Fuchsberger, M. Laumanns, and R. Zenklusen (2011). A new resource-constrained multicommodity flow model for conflict-free train routing and scheduling. Transportation Science, 45(2), 212-227.

Caimi, G., M. Fuchsberger, M. Laumanns, and M. Lüthi (2012). A model predictive control approach for discrete-time rescheduling in complex central railway station approach. Computers & Operations Research, 39, 2578-2593.

Chen, L. (2012). Real time traffic management in junction areas and bottleneck sections on mainline railways. School of Civil Engineering. College of Engineering and Physical Sciences, The University of Birmingham, UK.

Chen, L., F. Schmid, M. Dasigi, B. Ning, C. Roberts and T. Tang (2010). Real-time train rescheduling in junction areas. Proceedings of the Institution of Mechanical Engineers, Part F. J. of Rail and Rapid Transit. Vol. 224, no. 6, pp. 547-557.

Chiu, C. K., C. M. Chou, J. H. M. Lee, H. F. Leung, and Y. W. Leung (2002). A Constraint-Based Interactive Train Rescheduling Tool. J. Constraints, 7(2), 167-198.

Corman, F., A. D'Ariano, D. Pacciarelli, and M. Pranzo (2009). Evaluation of green wave policy in real-time railway traffic management. Transportation Research Part C, 17, 607-616.

Corman, F., A. D'Ariano, D. Pacciarelli, M. Pranzo (2012). Optimal inter-area coordination of train rescheduling decisions. Transportation Research Part E, 48, 71-88.

D'Ariano, A., D. Pacciarelli and M. Pranzo (2006). A branch and bound algorithm for scheduling trains in a railway network. European Journal of Operational Research, 183, 643-657.

D'Ariano, A., M. Pranzo, and I. Hansen (2007b). Conflict resolution and train speed coordination for solving real-time timetable perturbations. IEEE Transactions on Intelligent Transportation Systems, 8(2), 208-222.

D'Ariano, A. (2008). Improving real-time train dispatching: Models, algorithms and applications. TRAIL Thesis Series no. T2008/6, The Netherlands TRAIL Research School

D'Ariano, A., F. Corman, D. Pacciarelli, and M. Pranzo (2008). Reordering and local rerouting strategies to manage train traffic in real-time. Transportation Science, 42(4), 405-419.

D'Ariano, A. and T. Albrecht (2010). Running time re-optimization during real-time timetable perturbations. In: Timetable Planning and Information Quality (I. Hansen, ed.), pp. 147-157. WIT Press, Southampton.

Dessouky, M., Q. Lu, J. Zhao, and R. Leachman (2006). An exact solution procedure to determine the optimal dispatching times for complex rail networks. IIE Transactions, 38(2),141-152.

Fay, A. (2000). A fuzzy knowledge-based system for railway traffic control. Engineering Applications of Artifficial Intelligence, 13, 719-729.

Fay, A. and E. Schnieder (1997). Knowledge-based decision support system for real-time train traffic control. In: Lecture Notes on Economics and Mathematical Systems, Computer-Aided Transit Scheduling: proceedings, Cambridge, MA (Nigel H. M. Wilson, ed.), pp. 347-370. Springer-Verlag Berlin Heidelberg.

Hansen, I., J. Pachl (eds) (2008). Railway Timetable and Traffic – Analysis, Modelling, Simulation. Eurailpress DW Rail Media, Hamburg.

Higgins, A., E. Kozan and L. Ferreira (1996). Optimal Scheduling of Trains on a Single Line Track. Transportation. Transportation Research Part B, 30(2), 147-161.

Ho, T. K. and T.H. Yeung (2001). Railway junction traffic control by heuristic methods. IEE Proceedings Electric Power Application, 148 (1), 77–84.

Jacobs, J. (2004). Reducing delays by means of computer-aided "on-the-spot" rescheduling. In: Computers in Railways IX (J. Allan, C.A. Brebbia, R.J. Hill, G. Sciutto and S. Sone, ed.), pp. 603-612. WIT Press, Southampton.

Jacobs, J. (2008). Rescheduling. In: Railway Timetable & Traffic. Analysis Modelling Simulation (I. A. Hansen and J. Pachl, ed.), pp. 182-191. Eurailpress, Hamburg.

Kuckelberg, A. and E. Wendler (2008). Real-time asynchronous conflict solving algorithms for computer aided train dispatching assistance systems. In: Computers in Railways XI (J Allen, E. Arias, C. A. Brebbia, C. J. Goodman, A. F. Rumsey, G. Sciutto and N. Tomii, ed.), pp. 555-563. WIT Press, Southampton.

Lamma, E., P. Mello, and M. Milano (1997). A distributed constraint-based scheduler. Artificial Intelligence in Engineering, 11, 91-105.

Lusby, R., J. Larsen, M. Ehrgott, and D. Ryan (2012). A set packing inspired method for real-time junction train routing. Computers & Operations Research, 39, 2578-2593.

Mascis, A., D. Pacciarelli, and M. Pranzo (2002). Models and algorithms for traffic management of rail networks. Technical report DIA-74-2002. Dipartimento di Informatica e Automazione, Università Roma Tre, Rome, Italy.

Mazzarello, M., E. Ottaviani (2006). A traffic management system for real-time traffic optimisation in railways. Transportation Research Part B, 41, 246-274.

Ping, L.,N. Axin, J. Limin, and W. Fuzhang (2001). Study on intelligent train dispatching. In: Proceedings of the 4th IEEE International Conference on Intelligent Transportation Systems, pp. 949–953).

Rodríguez, J. (2007). A constraint programming model for real-time train scheduling at junctions. Transportation Research Part B, 41, 231-245.

Szpigel, B. (1973). Optimal train scheduling on a single track railway. Operational Research '72, Proceedings of the Sixth IFORS International Conference on Operational Research. IFORS, North-Holland Publishing, London, 343-352.

Tazoniero, A., R. Goncalves, and F. Gomide (2005). Fuzzy algorithm for real-time train dispatch and control. In: Proceedings of the 24th International Conference of the North American Fuzzy Information Processing Society, pp. 332–336.

Törnquist, J., J.A. Persson (2006). N-tracked railway traffic re-scheduling during disturbances, Transportation Research Part B, 41(3), 342-362.

Törnquist Krasemann, J. (2012). Design of an effective algorithm for fast response to the rescheduling of railway traffic during disturbances. Transportation Research Part C, 20, 62-78.

Tsamboulas, D., G.S. Yiotis and K.D. Panou (1999). Use of multicriteria methods for the assessment of transport projects. J. Transp. Eng., 125(5), 407-414.

Wegele, S. and E. Schnieder (2005). Dispatching of train operations using genetic algorithms. In: CD-ROM Proceedings of the 1st International Seminar on Railway Operations Modelling and Analysis (I. A. Hansen, F. M. Dekking, R. M. P. Goverde, B. Heidergott, & L. E. Meester ed.). Delft, the Netherlands.