ROBUSTNESS AND DELAY REDUCTION OF ADVANCED TRAIN DISPATCHING SOLUTIONS UNDER DISTURBANCES

Francesco Corman, Department of Transport and Planning, Delft University of Technology, Stevinweg, 1 - 2628 CN Delft, The Netherlands.

Andrea D'Ariano, Dipartimento di Informatica e Automazione, Università degli Studi Roma Tre, via della vasca navale, 79 - 00146 Roma, Italy.

Giovanni Longo and Giorgio Medeossi, Department of Civil and Environmental Engineering, University of Trieste, Piazzale Europa, 1 - 34127 Trieste, Italy.

ABSTRACT

Railway traffic is normally managed on the basis of a detailed plan of operations in order to optimize the use of infrastructure capacity by distribution of suitable time margins that can absorb minor delays. However, during operations major disturbances may influence the timetable feasibility and real-time adjustments of train timing and orders are required to assure compatibility with the real traffic situation and to limit delay propagation. This task is currently performed manually by dispatchers, while simple automated conflict detection and resolution systems are adopted to identify and solve train conflicts locally. Recently, innovative decision support systems have been developed to optimally reschedule trains in complicated railway areas with dense traffic and multiple delayed trains. In this paper the performance of such a system (ROMA) is evaluated, with regard to the robustness of its train dispatching solutions, by investigating the effects of small stochastic variations in input data on the quality of the dispatching solutions. An original simulation setup is proposed in which ROMA first computes train schedules that minimize delays in case of perturbed operations, and the resulting solutions are then validated by means of the microsimulation tool OpenTrack. Small stochastic variations are considered when evaluating a dispatching solution in order to simulate errors in input data. Robustness of the solutions is measured as variability of output delays for each scenario under the inserted stochastic phenomena. In most of the cases a First In First Out strategy is not able to solve conflicts without causing delay propagation. On the other hand, optimized dispatching solutions computed by ROMA offer quite a better delay reduction than straightforward dispatching rules. ROMA procedures, modelling and exploiting knowledge of future evolution of the network, also prove to be more robust to variability of input parameters than myopic rules using only local information.

INTRODUCTION

Railway operations usually follow a specified off-line plan (timetable) defined in advance. Timetables are normally designed months before actual operations. Time margins are included in the timetable in order to limit deviations from the plan and delay propagation.
Goverde and Odijk (2002) study the timetable stability, i.e., the ability to return to schedule operations as in the timetable after a disruption. Interconnected railway systems and time margins along train paths are modeled using max-plus algebra. Timetable robustness is evaluated by stability analysis, delay sensitivity and studying delay propagation.
Fischetti et al. (2009) propose a design of timetables with enhanced robustness in order to withstand deviations from normal operating conditions. A framework is proposed to compute and test timetables that, compared to the theoretically optimal solution, are more robust and only slightly less efficient. A combination of stochastic programming and linear programming allows the exploration of the trade-off between timetable efficiency, robustness and computation time.
In general, the timetable robustness can be defined as its ability to absorb small deviations through exploitation of existing time margins. However, no timetable is robust enough to cope with every possible disturbance in the network. The introduction of large time margins decreases heavily available capacity, resulting in unattractive services.
During operations, modifications to the existing operation plan are carried out by dispatchers in order to keep feasible operations (i.e. avoiding deadlocks), prevent delay propagation, and possibly return to the original timetable. Dispatchers limit delay propagation by adjusting dwell times, rescheduling train movements, changing routes and, in more serious cases, skipping scheduled stops or even cancelling services.
To help the dispatchers in their task, decision support systems have been recently developed (see, e.g., Giannettoni and Savio, 2004, Jacobs, 2004 and Luethi et al., 2007). Relevant information is given about the current traffic status in the network, alternative solutions and their future consequences.
In this context, Tornquist (2006) studies the use of heuristic procedures to find the key modifications to the disturbed timetable during operations. Trains are rescheduled with the goal of minimising the negative consequences of disturbances. Results of an experimental analysis of different objective functions are reported, showing results in terms of multiple performance indicators.
D'Ariano (2008) introduces a detailed mathematical model based on Alternative Graphs for the conflict detection and resolution problems that are frequently faced by dispatchers. An exhaustive search procedure is designed that detects and solves train conflicts in an optimal way within short computation times. The resulting decision support tool ROMA is proposed, that simulates precisely and optimizes train traffic flow over complex areas and heavy disturbances.
To evaluate the real behavior of a given timetable, simulation tools can be adopted, which can be microscopic or macroscopic. The latter tools consider railway lines as simple segments connecting stations, as in the tool Simone (Middelkoop and Bouwman, 2001). Due to this simplification, large areas can be managed in order to analyze timetable stability and delay propagation. Differently, microscopic tools are based on exact computation of running times and headways over each infrastructure element of the railway network, taking into

account signals, routes, and inter-train conflicts, as the tool OpenTrack (Nash and Huerlimann, 2004).

Huerlimann et al. (2009) use OpenTrack tool in order to compute timetable robustness measures. Performance indicators, like punctuality or average delays, are computed under stochastic disturbances, and their variability is assessed.

So far, robustness studies are usually carried on for timetables in order to evaluate macroscopically the performances of multiple scenarios during the planning stage. However, macroscopic models are not able to model precisely a railway system and the interactions between trains, especially when dealing with complex or large areas with dense traffic (see e.g. Caimi 2009).

This paper studies decision support systems and simulation tools for dispatching and evaluates their performances in terms of robustness and delay minimization. A robust dispatching system is able to deliver consistently good solutions that do not cause extra delay propagation in reaction to slightly different input conditions, i.e. the sensitivity to input parameters that are not known exactly. The robustness of dispatching solutions is measured by the variability of performance indicators and dispatching control actions when given input parameters (entrance times, dwell times, rolling stock characteristics) are not known precisely and therefore suffer small variations.

The optimization tool ROMA, computing dispatching solutions based on a detailed model of the infrastructure and train interactions, is combined with the microscopic simulation tool OpenTrack. A first check therefore is made to ensure that all relevant infrastructure and train dynamics data were the same in both systems. In fact, OpenTrack solves the motion equations to compute train dynamics, while ROMA system uses standard speed trajectories based on acceleration and braking tables. The choice to use two different systems enables us to draw more sound results, when evaluating optimized solutions and their robustness in a validated environment.

The remainder of the paper is organized as follows. Next section reports the approach followed to combine microsimulation with optimization. The dispatching procedures, the sources of uncertainty and the performance indicators are introduced. A section on the computational experiments follows. The last section presents conclusions and directions for future research.

APPROACH

ROMA and OpenTrack

The overall setup of the interaction of the two dispatching systems ROMA and OpenTrack is presented schematically in Figure 1. First, the same infrastructure, trains and timetable data has been made available to both systems. The following sections will explain more in detail the entrance delay instances and the variation in input parameters considered.

ROMA uses a detailed model of railway operations based on an alternative graph formulation, and can compute dispatching solutions according to a variety of scheduling algorithms, as explained in the following. The resulting dispatching solutions computed by ROMA are then implemented in OpenTrack as advisory orders between trains over all block sections. OpenTrack combines the train sequencing of ROMA with the given entrance times, infrastructure, timetable and train data to give in output a detailed schedule, specifying entrance time, running time and order of trains on each block section, route reservations and status of each signal, and that can be evaluated according to performance indicators.

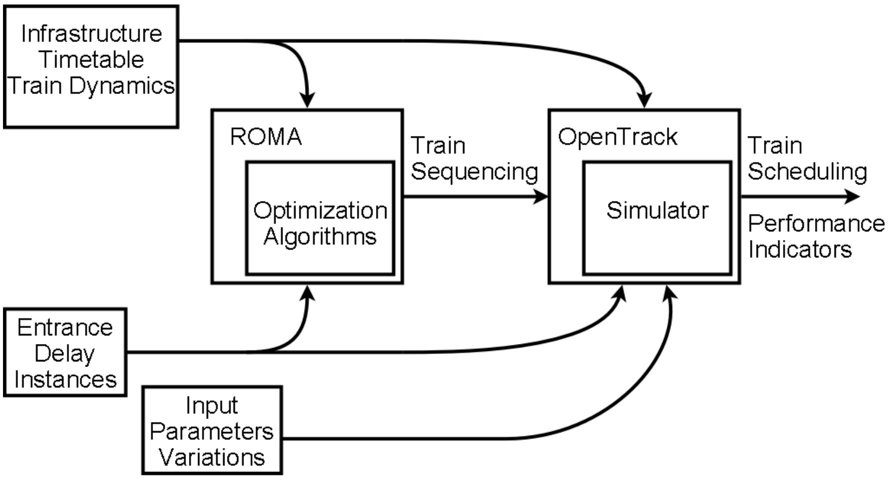

***Figure 1** – Interaction between ROMA and OpenTrack.*

Dispatching Procedures

The dispatching support tools used in this paper adopt blocking time theory (Hansen and Pachl, 2008) in order to thoroughly model the traffic flow and to precisely detect conflicts between train paths at a level of precision of seconds, especially in the proximity of interlocking areas, where multiple inbound and outbound routes exist. Four scheduling algorithms that are based on retiming actions (i.e., adjusting passing times of trains) and reordering actions (i.e., changing orders of trains) are considered. Note that the dispatching solutions BB and FIFO, introduced further below, are first computed in ROMA and then implemented in OpenTrack by imposing the entrance times of trains in the network and the train sequence over crossing and merging points.

FIFO: A common approach to dispatching is the well known First-In First-Out rule. When two or more trains claim the same shared piece of infrastructure, the train that comes first gets priority and passes first over it.

OT: The OpenTrack solution is computed by the available "optimize dispatching" function, which is a weighted FIFO where the highest priority is assigned to delayed trains. Train movements are checked for feasible operations locally, by looking ahead on the next infrastructure elements that are going to be traversed.

BB: The Branch and Bound algorithm of (D'Ariano et al., 2007) is used to compute near-optimal rescheduling solutions, with the objective of minimizing the maximum delay due to conflicts between consecutive trains. For this algorithm, the model adopted is the blocking time representation of interlocking areas proposed by (Corman et al., 2009b).

BB+OT: A combination of BB and OT is also proposed. The solution computed by BB is used as a starting point. The OpenTrack tool then changes train orders when route conflicts are found during the simulation due to stochastic variations of train positions and speeds.

Sources of Uncertainty

Various stochastic factors influencing railway traffic are analyzed in this work. A first stochastic phenomenon models entrance delay scenarios. We consider the actual time at which each train is expected to enter the dispatching area under study; this data is supposed to be known in advance by the solution algorithms. Initial delay distributions have been defined according to a previous study (Yuan, 2006) aiming at finding the best fit for real process-time distributions in The Hague main station. Real comprehensive data recorded during one month of operations are used to define Weibull distributions of entrance times of trains. Five delay scenarios are defined to represent average operations on a normal day, rather than heavily perturbed operations.

Stochasticity of other factors is studied in order to evaluate robustness under disturbances, assessing the impact of input variability (e.g., errors in measurements). Dwell times, entrance times and running times of trains are considered subject to small variations, leading to a total of 100 cases per scenario. For these stochastic variables, realization values are only known to OpenTrack, which makes use of that information when computing the OT and the BB+OT solutions. On the other hand, FIFO and BB schedule railway traffic according to the expected value of the varying input parameters.

Since these phenomena do not represent a process-time variability (which could be investigated analyzing real data), but an uncertainty between real and expected positioning, dwell time and performances, they have been modeled using Gaussian distributions. More in detail, deviations in entrance times are modeled on the basis of a Gaussian distribution with zero mean and a standard deviation of 15 seconds. This type of variations simulates imprecision in the tracking devices that communicate position and speed of each train entering the area, and may also take into account the fact that, while computing an optimized dispatching solution, the trains themselves are continuously moving in the network. Dwell times at intermediate stops are considered varying according to a Gaussian distribution with 10 seconds of standard deviation compared to the scheduled times. However, early departures are avoided. This variability models the impact of passengers at stations that generates small perturbations in the departure time, especially at major stations. The performance factor of the rolling stock material, influencing the running time, is modeled by a Gaussian distribution with 6% variance. Variability on rolling stock performance might be caused by different adhesions due to the weather conditions, different wear and tear on brakes and wheels, and driver behavior reaction to changes in signal aspects.

Performance indicators

The solution quality refers to the ability of keeping the traffic running without delays, avoiding uncontrolled spreading of delays. The following indicators of the solution quality of a schedule are introduced.

Punctuality reports the percentage of trains that arrive at a set of major stations or end points within a given threshold (3 or 5 minutes). Trains arriving later are considered as delayed. The resulting figure is an aggregated description of train operations, that may result in little significance when comparing different solutions with similar small entrance delays. Therefore other solution quality indicators are considered.

Cumulative delay reports the difference between scheduled and actual arrival times for all trains at a prescribed set of stations. This difference is computed only for those trains arriving late, avoiding considering early trains that may cancel out the impact of late trains.
The "Frequency of delay Index" *F* (Longo et al. 2008) has been also used. *F* includes both running time deviation and punctuality information, therefore it can be used as comprehensive parameter for quality of traffic and service measurement, while overcoming the weaknesses of the conventional reliability measures. The indicator weighs with different importance early and delayed events, and filters very high delays due to disruptions, to avoid quality underestimation due to unusual high disruptions. The index *F* is defined as follows:

$$F = \sum_i \left(\frac{N_i}{N} \times \frac{D_i}{P} \times f \right)$$

where N_i/N is the percentage number of trains arriving within a delay interval *i* with regard to the total number of trains, D_i is the amount of delay in interval *i*, *P* is the selected on-time bound and *f* is a weight coefficient. A kind of upper bound D_{max} is used for D_i to separate normal variability from large delays and therefore to limit the weight of these system failures on the indicator *F*. This study considers $f = 1$ for delayed trains (f_p), $f = -0.5$ for early trains (f_n) and $D_{max} = 20$ minutes. Figure 2 represents graphically the indicator *F*.

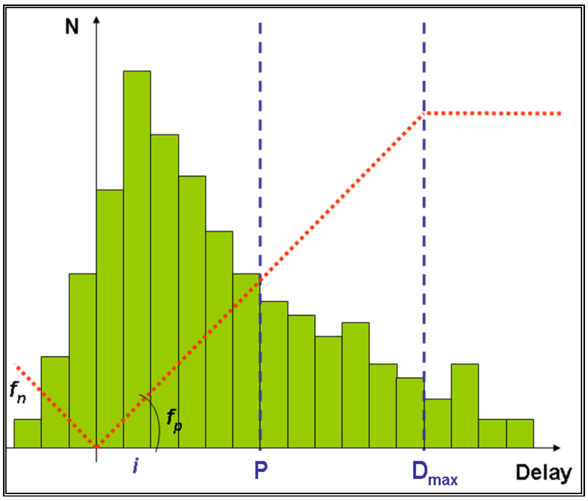

***Figure 2** – A graphical description of the parameters used in the index F*

The resulting index *F* is a synthetic percentage indicator, which is smaller as the traffic quality increases and shows values higher than 100 % for non-acceptable high variability and delays. The new indicator has been tested in different lines and nodes in Italy.
In order to focus only on delay propagation related to dispatching decisions, we consider in the computational results for the two performance indicators chosen (cumulative delay and *F*) only the variation (called delta in the following) between their values at the entrance and at the exit of the investigated network. In fact, the difference between the initial delay and the delay at the end of the trip expresses the system capacity to recover delays (stability). The delay propagation is due to the occurrence of consecutive delays and is implicitly pointed out if the delta delay for each train in the timetable is calculated and compared to the expected delay reduction allowed by running time margins.

When more stochastic simulations are performed, a measure of the variability in delay propagation is obtained, that expresses the robustness of the dispatching solution. Therefore the standard deviation of the delay reduction (delta cumulative delay) for each train is a synthetic measure of robustness, intended as the capacity of a dispatching algorithm to deliver solutions which do not cause unexpected delay propagation in event of small input variations. For each delay scenario the standard deviation is only measured for the subset of trains with delay larger than zero, in order to avoid considering in the robustness indicator the early-running trains.

TEST CASE DESCRIPTION

The dispatching procedures are tested on a complex dispatching area of the Dutch network (see Figure 3; for every station name, also an abbreviation is reported). The major station of Utrecht Central lies in the middle of the area considered, with 2 four-track and 3 double-track lines converging from both sides of the station. Minor stations delimit the area, resulting in a total diameter of about 20 km. Utrecht Central Station is a very busy station, with 20 platforms for passenger trains and a quite complex infrastructure topology. The 2008 timetable is considered, which features 80 trains per hour, from commuter trains to intercity and high speed trains on a regular-interval timetable.

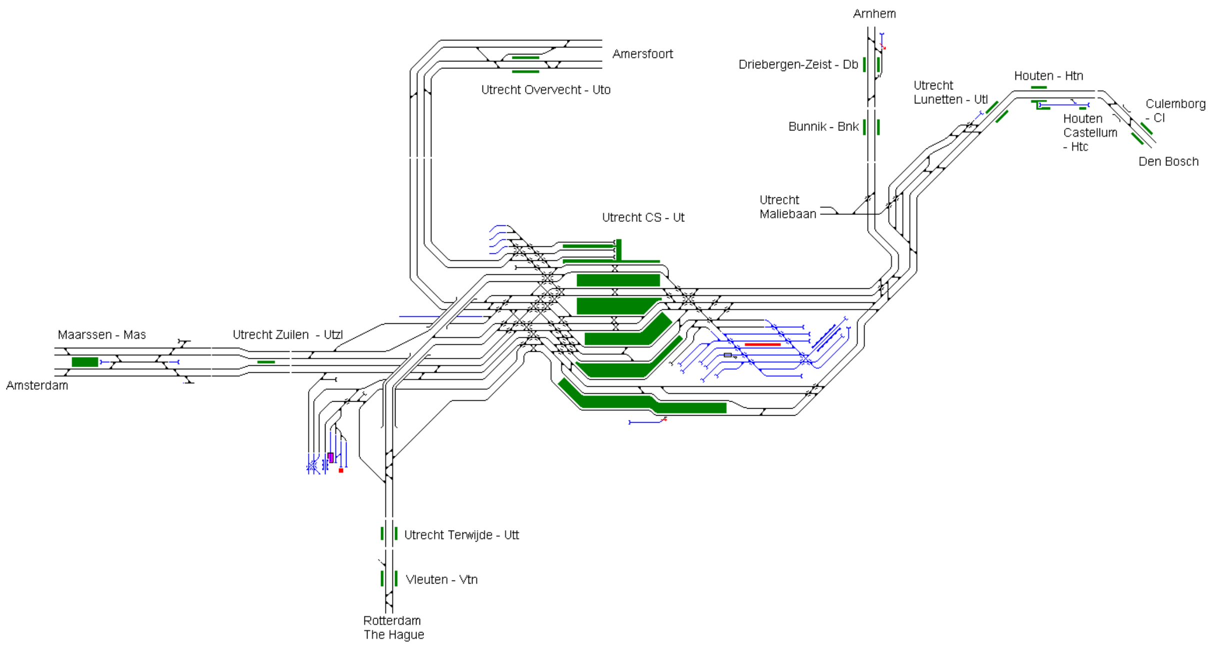

***Figure 3** – Utrecht Central dispatching area*

In order to check the feasibility of implementing the timetable solution computed by ROMA in OpenTrack a validation phase has been performed first. The two solutions are checked by comparing the scheduled and the simulated solution graphically, and analyzing the resulting detailed outputs, as shown in Figure 4 for an example situation. During this validation phase, orders, route blocking patterns and time separation between events are checked to be consistent in both systems.

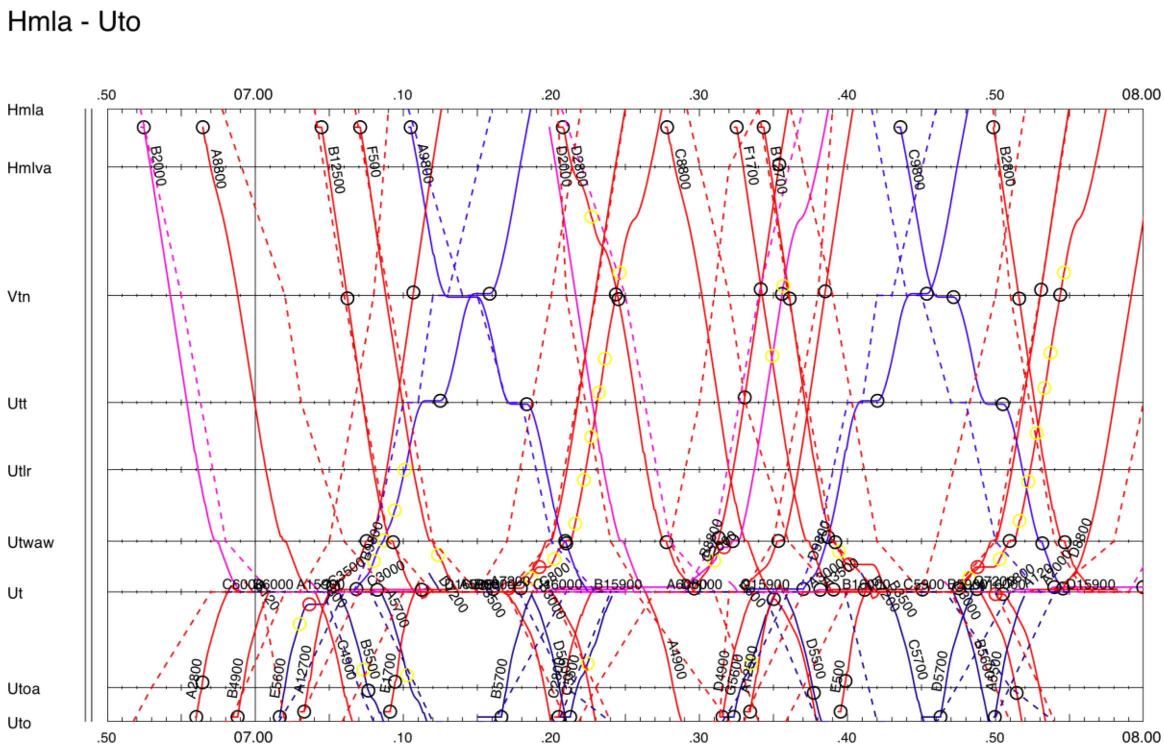

Figure 4 *– Scheduled (dashed) and simulated (solid line) train movements in OpenTrack.*

Practical Example

The differences among rescheduling algorithms can be first pointed out analyzing the resolution of some conflicts in a given scenario. For example in Scenario 3, train B3000 is strongly delayed at arrival in Utrecht CS. About 2 minutes before its departure, the slower D15900 departs on the same line. As a result, the B3000 increases its delay by over 3 minutes at arrival in Driebergen-Zeist. With BB, the D15900 must depart after the B3000: the B3000 reduces its delay by 197 seconds, while the D15900 is delayed by 65 seconds. In the same scenario, the B12500 departs from Vleuten with 221 seconds delay; at the home signal in Utrecht CS it has to stop for 170 seconds until the D7200 has entered. With the BB, the B12500 is allowed to enter first, reducing its delay by 287 seconds compared to FIFO; in this solution the D7200 has a delay increase by only 49 seconds.
Table 1 shows a detailed account of the situation for the 20 most delayed trains running, considering Scenario 3. Column 1 reports the train name, Column 2 the train route, specified by the station of origin and destination, Column 3 the entrance delay at first station (in seconds). Column 4 -7 report instead the delay at the last station considered (in seconds), as computed by the different rescheduling algorithms.

***Table 1** – Example of simulation results: comparison of delays at last station with different rescheduling algorithms*

Train	Route	Entrance delay (sec)	Delay at the last station (sec)			
			FIFO	OT	BB	BB+OT
A9800	Vtn - Ut	1024	823	823	823	823
B3000	Mas - Ut - Db	800	856	856	669	669
D4900	Uto - Ut	715	575	575	575	575
B4900	Uto - Ut	610	459	459	459	459
B12500	Vtn – Ut - Uto	221	454	187	187	187
C2000	Db – Ut - Vtn	459	302	302	302	302
A16000	Cl - Ut	385	289	289	289	289
C4900	Ut - Uto	367	217	217	217	217
A800	Ln – Ut - Mas	355	285	285	285	285
B5500	Ut - Uto	310	205	205	205	205
B2000	Vtn – Ut - Uto	247	182	182	182	182
D9800	Ut - Vtn	239	170	170	103	103
D3500	Mas – Ut - Ln	173	126	126	126	126
B12700	Vtn – Ut - Uto	147	9	9	9	9
A7200	Ut - Mas	135	85	85	85	85
A5500	Uto - Ut	128	31	31	31	31
A2800	Uto - Ut	103	-47	-47	-47	-47
D5500	Ut - Uto	101	-58	-58	-58	-58
D7200	Mas - Ut	101	-12	-77	-12	-12
A8800	Vtn - Ut	90	12	12	12	12
C6000	Htn - Ut	85	-43	-43	-17	-43
D5900	Ut - Db	81	-38	-38	-38	-38

Average Performance

The average results over all scenarios studied are now described. First the results obtained for the FIFO procedure are discussed, considered as reference practical dispatching rule.
FIFO solutions present, on average, 18 delayed trains, a value for delta cumulative delay of 1285.6 seconds, and a value for delta F of -194 %. The stochastic variations in input parameters result in a standard deviation on the output delay of 11.6 seconds. The small output variations are justified by the time margins existing in the timetable.
Table 2 shows performance indicators of the other dispatching procedures described in this paper when compared to those of the FIFO procedure. Respectively, Columns 2-4 report the

average results obtained by the "optimize dispatching" module of OpenTrack (OT), the branch and bound algorithm (BB), and the combination of BB with OpenTrack (BB+OT). The first three rows present the variation in the number of delayed trains, the variation in delta cumulative delay (in seconds) and the variation in delta *F* (in %). The last row reports the variation in the standard deviation of the delta cumulative delay (in seconds), compared to the standard deviation of the solutions computed by FIFO.

Regarding the solution quality indicators (first three rows of Table 2), FIFO dispatching measures generate less delayed trains than the other algorithms but the largest delta cumulative delay and delta *F*. For the latter two indicators, the procedures based on BB (either BB or BB+OT) achieve the best scores. Precisely, the BB+OT procedure is the best configuration due to the OT flexibility to adjust the BB solution to the actual realization (even if no more than a train per delay scenario is adjusted by OT). Analyzing the relation between the infrastructure layout and the timetable structure, most conflicts are avoided by flyovers and train movements planned along directions that are almost independent.

This is due to the fact that FIFO considers a local view to solve conflicts, while BB is an advanced algorithm using the FIFO as starting solution and improving it by an exhaustive search exploiting global information on the future evolution of the network, available within ROMA.

Table 2 *– Average performance of the algorithms, difference with the FIFO solutions*

Dispatching procedure	**OT**	**BB**	**BB+OT**
Increase in # of delayed trains	0.4	0.8	1
Reduction delta cumulative delay (sec)	58.8	137	158
Reduction delta *F* (%)	10.4	18	19.8
Variation in std dev delta cml delay (sec)	+2.5	-0.4	+0.4

Regarding the robustness quality indicator, BB outperforms the other dispatching procedures. In fact, OpenTrack can adjust train dispatching to the exact realization of the stochastic parameters, but the dispatching rules used to take decisions are based on a myopic and local view of the problem, resulting often in suboptimal solutions.

The results of Table 1 point out the benefits of optimal delay minimization. However, when comparing the average results obtained for each simulation scenario, it can be noticed that only 2.2 trains out of 80 trains are changed in BB compared to FIFO. Moreover, the number of conflicts is small, especially if compared to the high traffic density on the network. In other words, only very few conflicts are solved by rescheduling algorithms differently.

Therefore, normal delay distributions result in only a relatively small number of conflicts, whose solution could be more complex than a simple FIFO. Thus, the benefits of an optimized solution could be better pointed out when the methodology is tested under a different, more critical, combination of infrastructure topology, timetable and delays. The solutions computed by advanced scheduling algorithms, such as BB, lead anyway to smaller delays, and are more robust than solutions based on local conflict resolution decisions. The obtained results confirm that a prediction of the future status of the network is needed when computing optimized rescheduling decisions.

CONCLUSIONS

This paper presents a quantitative study on dispatching solutions that reduce delay propagation at network scale, computed by advanced dispatching support systems and validated by microscopic simulation in OpenTrack. It is focused on the analysis of schedule robustness under disturbances. Robust solutions implemented in a microscopic simulation tool require few adjustments in order to react to real-time changes. On the other hand, non-robust decisions are quite sensitive to un-modeled dynamics or variability of the input parameters. In general, the optimization of the delay reduction of dispatching solutions is a goal conflicting with their robustness to parameter variations. The trade-off between solution quality and robustness of dispatching actions is investigated on light delay scenarios. We conclude that on the fly schedule adjustments are relevant in order to cope with the variability of input parameters. However, further computational studies are necessary in order to fully evaluate the impact of more effective dispatching strategies that consider the future evolution of traffic flow and delay propagation, rather than taking myopic and local decisions. Future works should also include a more extensive assessment of the real-time variability of input parameters, plus an analysis of heavier delay scenarios and larger railway areas. When a common interchange format between microsimulation systems is defined, other dispatching actions, such as advanced speed advices to drivers (Corman et al., 2009a), can be considered in an extensive evaluation of advanced dispatching support tools. Another interesting comparison could be drawn when analyzing the actual dispatching decisions taken by human dispatchers on historical basis. This could lead to a better evaluation of the benefits of advanced dispatching systems compared to actual operations.

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