Smooth and Controlled Recovery Planning of Disruptions in Rapid Transit Networks

Luis Cadarso*, Angel Marín*, and Gábor Maróti**,***

*Technical University of Madrid, Plaza Cardenal Cisneros, 3, 28040 Madrid, Spain
**Process Quality and Innovation, Netherlands Railways, 3500 HA, Utrecht, Netherlands
*** VU University Amsterdam, De Boelelaan 1105, 1081 HV, Amsterdam, Netherlands

1. Introduction

This paper studies the integrated timetabling and rolling stock re-scheduling problem in the disruption management of dense passenger railway networks.

During the daily operations of a dense passenger railway network, incidents may cause the traffic to deviate from the planned operations. Such irregular events, called disruptions, lead to delays and cancellations that make the schedule unfeasible. In such a situation the operator needs to adjust the timetable and the rolling stock assignment for the time interval of the disruption, and to carry out further recovery steps in order to get back to the original schedules.

In the current railway practice, the recovery problem is solved in a sequential manner (Jespersen *et al*., 2009). When a disruption occurred, first a new timetable is computed accounting for rolling stock availability; then, the rolling stock schedules are modified such that the rolling stock is balanced before the end of the day (Budai *et al*., 2010). Walker *et al*. (2005) are among the first ones to deal with the integration of timetabling and resource scheduling in disruption management.

To produce recovery plans is a complex task since the re-planning has to be done in real-time (Kroon and Huisman, 2011). A complicating issue with disruptions is the fact that the duration of the disruption is usually not known exactly and that the status of the railway system is changing at the same time. As a consequence, the dispatchers apply rescheduling actions several times, always taking the latest available information into account (Nielsen *et al*., 2012).

The disruption management process has several objectives. The first goal is to provide the best possible service quality. The second goal aims at easing the rescheduling process by minimizing the differences between the original plan and the recovery plan. Third, the operators often want to quickly return to the original plan once the disruption is over.

This paper focuses on the latter two objectives, and we measure the quality of a recovery plan by two metrics: the number of schedule changes and the length of the recovery period. A recovery plan with a huge number of schedule changes might be impractical for the operator. Hence, *smooth* recovery plans defined as plans with a low number of schedule changes must be provided. Also, operators often want to recover before a certain point in time (e.g., the peak hours); therefore, operators should be able to *control* when the recovery is finished.

In this research, the timetable and the rolling stock schedules are jointly optimized, and we account for the effects of the disruption on the passenger demand with a model for the passengers' behavior.

The contributions of this paper are summarized as follows.

- We develop an optimization model to be applied in case of disruption that simultaneously deals with timetabling, rolling stock scheduling, schedule changes and recovery period length decisions, also accounting for the changes in the passenger demand.
- We control the length of the recovery period and limit the number of the schedule changes.
- We report computational tests on problem instances of the Spanish rail operator RENFE.

2. Problem Description

The *railway network* is composed of stations and arcs between them. The arcs consist of one or two pairs of rails. The impact of a disruption is a change in the network topology and in the resource availability. The *demand* is realized through available paths in the network; passengers choose their paths based on the expected travel time.

We distinguish two types of *train services*: the planned train services and the emergency services. Planned trains are scheduled for the normal (undisrupted) situation; emergency trains are scheduled during the disruption to alleviate its negative effects in passengers. We also consider empty movements in order to re-position rolling stock between depot stations.

The rolling stock units are self-propelled, they all have driver seats at both ends. The units are available in several *rolling stock types*. Units of the same type can be attached to each other to form trains compositions. Shunting operations are only performed at depot stations.

3. Model Formulation

The Integrated Smooth and Controlled Re-scheduling Model (ISCREM) aims at computing the timetable and the rolling stock schedule for a disrupted rapid transit network. The ISCREM is based on the model proposed by Cadarso *et al*. (2013). The novelty of the current paper lies in the following: (*i*) different penalties for schedule changes depending on their initial time are used; (*ii*) the length of the recovery period is controlled; and (*iii*) the number of schedule changes simultaneously operated is limited.

The most crucial decision variables are $x_{l,c} \in \{0,1\}$, defined for $l \in L, c \in C$. Their values indicate whether composition $c \in C$ is scheduled for service $l \in L$. In order to develop smooth recovery plans, $\sigma_{t'}^{t} \in Z^{+}$ variables are introduced. Their values indicate the number of schedule changes that started during time period t' and that are being performed during time period t. Consequently, $\sum_{t' \in T} \sigma_{t'}^{t}$ represents the total number of schedule changes that are performed during time period t. The recovery length is controlled through variables $\Gamma_t \in \{0,1\}$. These variables enable the operator to control the length of the recovery period.

The model minimizes a combination of system-related and service-related criteria subject to several constraints. The purpose of the constraints is summarized as follows. As for the timetable, headway times are enforced, emergency trains are inserted, and direction of the traffic on the disrupted arc is decided. The passenger demand is linked to the capacity of the allocated train units. As for the rolling stock, the amount of used rolling stock is limited, each trip gets a composition assigned, and the storage and shunting capacity of the stations is controlled. The variables for the schedule changes are linked to other variables. The operator may require explicit limits on the number of schedule changes and on the length of the recovery period.

Our model treats the demand heuristically. The model considers demand on the arcs. Passengers are *denied* whenever the demand of an arc exceeds the allocated capacity. Cadarso *et al*. (2013) justify this heuristic demand treatment by giving empirical validation: in spite of the simple per-arc demand structure, the model treats the overwhelming majority of passengers accurately.

4. Computational Results

Our experiments are based on realistic cases drawn from RENFE's regional network in Madrid for 2008. This case study features a disruption where one of the two tracks between two stations is blocked:

trains in different directions must share the remaining track. Also, some trains that were supposed to pass may turn back instead of entering the disrupted segment. The disruption starts at 8:00 a.m. and it lasts 120 minutes. We restrict the network to the lines affected by the disruption. The restricted network features 46 stations, and about 12,000 trips in 760 timetable services. About 530,000 passengers use the restricted network, 47,000 of which are directly affected by the disruption. The network has double tracks on all segments.

Figure 1 shows the number of schedule changes for two recovery plans for the above described disruption: a non-controlled-non-smooth recovery plan on the left and a controlled-and-smooth recovery plan on the right. Note that the vertical axis scale of the two plots differs. The number of schedule changes and the length of the recovery period are dramatically lowered and shortened, respectively (from 5537 changes finished by 21:26, to 696 changes finished by 10:45). However, operating costs increase by 1%, and the percentage of unsatisfied demand increases by 0.32% point (from 3.91% to 4.23%). At this small price, the operator is able to apply more practical and efficient recovery plans.

5. Conclusions

In this paper we study the recovery problem of rapid transit networks. The main contribution with respect the literature is that our approach simultaneously decides on the timetable and on the rolling stock schedule, also accounting for the passenger demand behavior, while minimizing and limiting schedule changes and controlling the length of the recovery period. Our computational times for realistic cases drawn from RENFE amount to a few minutes which is sufficiently close to the needs of real-time decision making. This is a great advantage with respect to the current system of manual re-planning where planners work under great time pressure.

6. References

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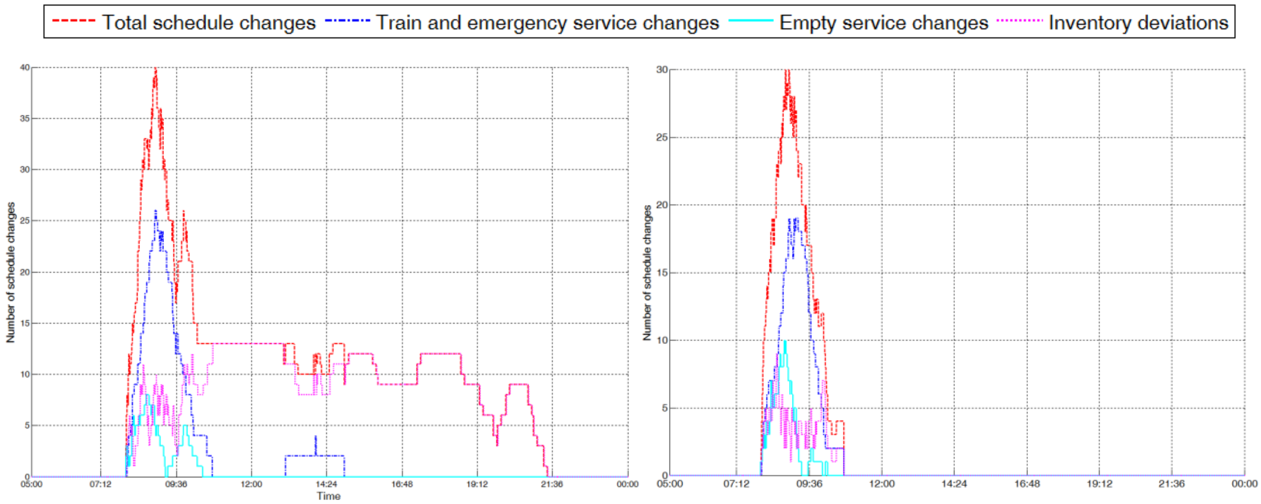

Figure 1: Number of schedule changes for a non-controlled and non-smooth recovery plan (on the left) and for controlled and smooth recovery plan (on the right)

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