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A demand-based weighted train delay approach for rescheduling railway networks in real time

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ABSTRACT

Rail systems are highly complex and their control in real time requires mathematical–computational tools. The main aim of these tools is to perform swift optimal rescheduling in response to disruptions or delays caused by events not foreseen in the original plans, so that there is no knock-on effect on other services due to these primary delays. This paper proposes a novel weighted train delay based on demand approach based on the alternative graph concept for rescheduling passenger train services. This problem is formulated as a binary integer linear programming problem which tries to maximize consumer satisfaction by minimizing total passenger delay at destinations. A heuristic method, the so-called *Avoid Most Delayed Alternative Arc* (AMDAA) algorithm, is proposed to solve the model. AMDAA is an adaptation of *Avoid Maximum Current Cmax* (AMCC) developed by Mascis and Pacciarelli (2002) to the new model. A numerical comparison is carried out with AMDAA, a Branch-and-Cut method, AMCC and the heuristic *First Come First Served* (FCFS). Numerical research carried out with data from the Renfe Cercanias Madrid rail network (Spain) shows the high computational performance in real applications of the algorithms and the suitability of this weighted train delay based on demand model versus the classical makespan minimization approach.

1. Introduction

Currently, railway systems, both of goods and of passengers, represent one of most heavily used forms of public transport in developed countries, and demand is constantly increasing. Rail networks are expanding and growing, creating very large, complex systems.

New strategies for increasing capacity are needed, including the building of new infrastructures and the improvement of existing ones. The improvement of these railway infrastructures requires heavy economic investment which may not be possible. Therefore, production-based strategies for increasing capacity by allowing more trains to be operated on the same infrastructure, or by train scheduling, are being developed. A key task for railway systems is to create an optimal timetable capable of satisfying all the requirements for assessing the proper working of the system.

The railway rescheduling problem has been defined in an online context without uncertainty, to try to handle an unexpected disruption that occurs in real time, Kraay and Harker (1995) and Narayanaswami and Rangaraj (2013). This situation may lead the railway system to be incapable of properly addressing the requirements of the system or satisfying the original timetable and requires network recovery to be achieved in a short time. Recovery can be carried out attempting to return train to their original timetables or generating new temporary timetables for the remainder of their journeys.

In literature about train timetabling problem, the demand is a key factor and it is exhaustively considered (Cacchiani and Toth, 2012). On the other hand, in rescheduling the existence of a passenger dissatisfaction-based timetable is assumed so its main objective is to recover the system to the pre-established timetable, not directly considering demand in this phase. In this paper is assumed that demand data is available and can be taken into account in the process of recovering the railway system.

The paper is organized as follows. Section 2 discusses previous research in rescheduling, Section 3 defines the concept of alternative graphs and the new approach proposed, Section 4 presents the heuristic algorithm used for solving the rescheduling problem, in Section 5 several computational experiments are reported to compare these solutions, and finally Section 6 concludes with a discussion of our findings and future work.

2. Past research

Many studies are currently being carried out to solve problems related to railways, we refer the reader to Caprara et al. (2002, 2007) and Cordeau et al. (1998) for surveys in railway optimization. Focussing on the train-conflict resolution problem with the

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aim of improving the quality of the service offered, the main strategies followed are train timetabling, train dispatching, train platforming and train routing problems (Lusby et al., 2011).

This paper is focused on train-conflict resolution in real-time. Bilevel programming is a general framework used for describing this problem. The lower level problem defines an equilibrium between railway services' supply and demand. The supply model represents the infrastructure, capacities, operating rules, safety rules and design of the train services of the rail network. This model provides the real timetable when a disruption occurs following a predetermined rescheduling strategy. The demand model represents user behavior in the railway network.

The supply model is modeled as train scheduling (TS) at a microscopic level which represents how the trains move through the network. The demand model takes into account the decisions of passengers at a macroscopic level including re-routing or disconnecting strategies which consider the timetable and the possible connections between trains. This problem is known as Delay Management (DM).

The upper level problem represents rescheduling decisions within the railway network. The main points of view in the literature for modeling the objective function are the minimization of weighted train delay or the minimization of train delays. The first approach needs to include a demand model which increases its complexity when it is solved in real time. Because of this in most cases the approaches found in the literature are focused on the TS.

Table 1 shows a classification of the literature according to the approach followed.

A mathematical tool widely used for modeling the TS problem is the so-called *alternative graphs* method described by Mascis and Pacciarelli (2002). These graphs represent the feasible moves for an individual train in time and space as nodes and fixed arcs and the conflicting train paths as a pair of alternative arcs. Any solution of the graph requires that one of each alternative arc pair be selected. This approach represents the train timetabling problem as job-shop scheduling, where the railway scenario is analogous to a shop with blocking and no-waiting behavior. This formulation will lead to a minimization of the makespan of trip times in a railway context.

The main difference with the alternative graph compared to other approaches presented in the literature is the detailed but flexible representation of the network topology with regard to railway signals and operational rules. This approach can easily incorporate a number of traffic regulation rules and constraints relevant to railways, which are rarely taken into account in the literature, as observed by D'Ariano (2008).

Mascis and Pacciarelli (2002) proposes a heuristic algorithm that tries to reduce the computational costs of solving the complete alternative graph called *Avoid Maximum Current Cmax* (AMCC). This algorithm compares in each iteration two alternative arcs and avoids the arc whose selection would result in the worst solution based on the evaluation of each path.

Mazzarello and Ottaviani (2007) apply this formulation for dynamic rescheduling after delays, minimizing delays and fuel consumption. Furthermore D'Ariano et al. (2007a) apply this concept to a rescheduling problem improving AMCC algorithm with the inclusion of the concept of *static implications*. D'Ariano et al. (2008a) and Corman et al. (2010, 2011b) use alternative graphs for re-routing trains in real time. D'Ariano et al. (2008b) test the same model for dynamic timetabling for dispatching support. It is also possible to compute the optimal speed profile for each train using this model (D'Ariano et al., 2007b; Corman et al., 2009). Another approach of rescheduling presented by Corman et al. (2011a) is to modify the objective function of the model including classes of priority for the trains.

Corman et al. (2012b) deals with the coordination of multiple regional control centers. These authors demonstrate that the coordination problem can be ideally solved with a Branch and Bound procedure.

Tornquist Krasemann (2012) detects that for certain scenarios it is difficult to find good solutions within seconds using a Branch-and-Cut approach. This paper proposes a greedy algorithm which effectively delivers good solutions within the permitted time.

Currently a growing interest exists in how to represent the demand decisions, leading to the development of models that combine the TS and DM problems.

Dollevoet et al. (2009) and Schachtebeck and Schöbel (2007) propose to use an approach aimed at minimizing the sum of all passenger delays plus the sum of all missed connections. Schachtebeck and Schöbel (2007) add capacity constraints to the Delay Management formulation.

Corman et al. (2012a) describes a bi-objective TS to minimize both the delay of the trains and the number of missed connections.

Kanai et al. (2011) deals with DM and TS problems combining simulation and optimization. The simulation part consists of a train traffic simulator and a microscopic passenger flow simulator which traces the behavior of passengers one by one. The optimization approach minimizes passenger dissatisfaction.

Almodóvar and García-Ródenas (2013) proposes a model for timetable rescheduling in emergency cases, reallocating trains/buses in real time to other service lines. This model assumes that passengers use travel strategies and waiting passengers are loaded at trains/buses on a first-come-first-served basis. The infrastructure restrictions are not taken into account by the model.

Dollevoet et al. (2012) presents an integrated approach of DM and TS models. It determines which connections to maintain and

Table 1
Summary of related studies on TS and DM grouped by characteristics considered.

	TS			DM	
Reference	Re-routing	Sequencing	Speed change	Passenger delays	Connections
Kraay and Harker (1995), Tornquist and Persson (2007), Min et al. (2011), D'Ariano et al. (2008a) and Corman et al. (2010, 2011b)	X				
Mascis and Pacciarelli (2002) and D'Ariano et al. (2007a)	X	X			
Mazzarello and Ottaviani (2007)	X	X	X		
D'Ariano et al. (2008b), Corman et al. (2011a, 2012b) and Tornquist Krasemann (2012)		X			
D'Ariano et al. (2007b) and Corman et al. (2009)		X	X		
Dollevoet et al. (2009) and Schachtebeck and Schöbel (2007)		X		X	X
Corman et al. (2012a), Kanai et al. (2011) and Dollevoet et al. (2012)		X			X
Almodóvar and García-Ródenas (2013)	X			X	
Cadarso et al. (2013)		X		X	
Wang et al. (2013)	X			Passenger comfort Fuel consumption	