INTEGRATING TIMETABLE RECOVERY AND ROLLING STOCK RESCHEDULING

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ABSTRACT

During daily operations of a railway network incidents may cause the railway traffic to deviate from the planned operations. In this situation new plans must be designed in order to operate under the new conditions and to recover network operations to the usual plan once the incident has finished.

In this work, timetable and rolling stock rescheduling are addressed in an integrated way. The incidence may become the planned timetable inefficient or even impossible to operate. Thus, a new service schedule must be designed minimizing some operator and passengers costs.

As far as the timetable is changed the rolling stock assignment must be revised. The rolling stock rescheduling assigns the different material types to the previous redefined services and decisions about the aggregation and disaggregation of the convoys in the depot stations are taken.

We illustrate our model using computational experiments drawn from RENFE (the main Spanish operator in suburban trains of passengers) in Madrid, Spain.

Keywords: Rolling Stock Rescheduling, Timetable Recoverability, Integration.

INTRODUCTION

During daily operations of a railway network incidents may cause the railway traffic to deviate from the planned operations. Such incidents include infrastructure blockage, failing rolling stock and crew shortage. In case of incidents the railway operations are said to be disrupted. A disruption restricts the railway operation by cancelling or delaying some trains. In a disrupted situation the resources must be rescheduled according to the restrictions imposed by the disruption. The disruption management process includes the following major tasks:

1. Adapt the timetable according to the restrictions imposed by the disruption.
2. Reschedule the rolling stock to cover the disrupted timetable.
3. Reschedule the crew to serve the adapted rolling stock schedules.
4. Reschedule passengers flow.

The four tasks are interdependent but are often solved sequentially due to time restrictions and due to the intractability of an integrated approach. In this study we wish to investigate the possibilities of a closer integration of the timetable, rolling stock and passengers recovery; adapting the timetable and the rolling stock schedules.

We can have different disruption types in the network, which can lead in different ways of treating the recovery problem:

1. Rolling Stock shortages: it may include train delay due to, for example, longer than scheduled shunting operation times due to lack of resources, or due to longer than expected passenger embarking and disembarking times. For a first approximation we can deal these disruptions with swapping trains trying to avoid changes in the timetable. In this way, the disruption can be treated from the routing problem.
2. Stations and arcs capacity shortages: these disruptions can be stronger than the previous one, for example, an arc closed. In this case a new timetable must be developed.

In the next sections the mathematical model for integrated timetable and rolling stock rescheduling are described in detail. The core of the model is to decide the departure time of each service and the rolling stock assigned to the services. The rolling stock assignment is subject to a number of constraints on shunting possibilities at the stations and the availability of rolling stock. These constraints depend on the railway and its area of interest; specifically if it is an urban or interurban network, as in RENFE (the main Spanish operator in suburban trains of passengers) and NS (the main Dutch operator in interurban trains of passengers) cases.

State of the Art

A large number of publications address Rolling Stock Scheduling: We refer to Caprara et al. for a comprehensive overview. Other references are Alfieri et al. (2006), Fioole et al. (2006) and Peeters and Kroon (2008). They model the rolling stock assigning to timetable services while optimizing the capacity, robustness and efficiency of the schedules.

Other references are about the dispatching of trains trough dense network: Törnquist (2005) provides a review of the railway scheduling and dispatching, classifying the models respect to problem type, solution methods and type of evaluation. D'Ariano (2008) considers the routing and sequencing trains for given routes and improving the solution locally rerouting some trains, including rolling stock and passenger connections. Different disturbances are analyzed, including train delays and blocked tracks.

Algorithmic methods that have been developed so far for increasing the robustness of rolling stock and their rescheduling based on railway operators using planning rules based on experience, Abbink et al. 2004, Maróti (2006), and Fioole et al. (2006), as follows:

- Rolling stock circulations are often line based. As a consequence, there is a lower probability that delays of trains can spread from one line to another. Each line is operated by few rolling stock types only. This increases the recovery capacity of the system.

- Long return times are used at line depots, so that delays of arriving trains can be absorbed. In them the rolling stock duties can be exchanged, which permit repairs the rolling stock duties, when they have been disrupted.

- The number of shunting operations for increasing or decreasing the capacities of trains is as small as possible. More shunting operations may be detrimental for the robustness, since they increase the utilization of the station recourses.

- A number of spare rolling stock units are strategic located at deposits. The price is the empty trains and the necessity of more trains.

A heuristic approach to re-build a passenger transportation plan in real-time was proposed by de Almeida et al. (2003). This approach is intended for the management of major disruptions, where the track capacity is highly reduced. After computing an initial score for each train, a greedy algorithm consisting of several consecutive steps is run in order to select trains and to assign them to a valid consist. It is assumed that consists are not changed throughout the overall disturbance.

As a consequence of the first applied measures during a disruption, the rolling stock units may not finish their daily duties at the locations where they were planned prior to the disruption. This is not a problem if two units of the same type get switched: rolling stock units of the same type can usually take each other's duty for the rest of the day. More likely, however, the numbers of units per type ending up in the evening at a station differ from the numbers of units per type that were planned to end up there.

Cadarso and Marín (2010) focus on the railway rolling stock circulation problem for rapid transit networks, where frequencies are high and distances are relatively short. Although distances are not very large, services' times are high due to the great number of intermediate stops in order to attend the passenger flow. A complicating issue is the fact that the available capacity at depot stations is very low, and both capacity and rolling stock are shared between different train lines. This forces the introduction of empty train movements and rotation maneuvers, in order to ensure both station capacities and rolling stock availability.

Unless expensive empty trips are used, the traffic on the next day is influenced by the disruption. Modifications of the schedules for the busy peak hours of the next morning are highly undesirable. Therefore additional measures are to be taken so that the rolling stock balance at night is as close to the planned balance as possible. This problem is studied by Maróti (2006) and Budai et al. (2008). One of the solution approaches is based on the principle of augmenting paths from network flow theory. Also heuristic methods are described.

The literature on real time rolling stock rescheduling is scarce, we mention here a number of publications that consider problems similar to the one addressed in this paper. Jespersen-Groth and Clausen (2006) consider the problem of reinserting canceled train lines after a disruption. They formulate a MIP model which minimizes train cancellations on the disrupted lines.

Budai et al. (2008) consider the rolling stock balancing problem. This is the problem of rolling stock rescheduling so that it ends up at the correct stations at the end of the day. Their models take the exact order of the rolling stock units in the trains into account and minimize the number of rolling stock units that end up at different stations than planned. The rescheduling is subject to a number of constraints on capacity demand and shunting possibilities. The problem is solved for fairly large instances by iterative heuristics whose short running times are attractive for real time usage. However, the model does not take the stochastic nature of real time operations into account.

L.K. Nielsen, L. Kroon and G. Maróti (2008) deal with real-time disruption management of railway rolling stock. The goal is to adjust the original rolling stock schedules for the updated timetable. They defined the online variant of the rolling stock rescheduling where the uncertainty about the duration of the disruption is modeled by a sequence of timetable updates. In order to deal with such uncertainties they proposed a rolling horizon framework as a solution approach. In this framework they consider rolling stock decisions within a certain horizon of the time of rescheduling. The schedules are then revised as the situation progresses and more accurate information becomes available. First, the timetable is updated by cancellations of trains, which is penalized joint with the modifications of the shunting process as well as the end-of-day rolling stock off balances, which are considered in the second step about the rolling stock rescheduling. Based on the undisrupted rolling stock circulation, they define target inventories, and minimize the deviation from these targets. Arguably, the heuristic target becomes more accurate as the current horizon approaches the end of the day. Therefore the objective coefficients of the off balances increase as the horizon shifts ahead in time.

PROBLEM DESCRIPTION

In this section, the problem is described in detail. First, the railway infrastructure is introduced. Next, we describe the train services, and finally, passenger demand is introduced.

Railway Infrastructure

The railway infrastructure is described by stations and directed arcs between stations. Let S be the set of stations and let A be the set of arcs. Each arc $a \in A$ is from departure station $ds_a \in S$ to arrival station $as_a \in S$. Some stations have depots attached and at those stations it is possible to change the assignment of rolling stock to trains. $SC \subset S$ denotes the set of depot stations.

Time is discretized into a set of time intervals T. Each time interval or period $t \in T$ represents a certain interval in time, for example from 8:00 to 8:01. We use two different approaches to discretize the time. The second one is represented by $\tau \in T$; the difference is that the time span is greater in this second approach.

Each station has a certain capacity for arriving and departing trains, this is represented by limiting the number of arriving and departing trains over a period of time. Let TS_s represent the time periods for which the number of arrivals and departures are restricted at station $s \in S$. Each period is represented by a set of time intervals $\tau \in TS_s$, and the capacity of s is denoted by $sq_{s,\tau}$. Arcs are capacitated in a similar way; $q_{a,t}$ denotes the maximum number of trains that can use arc a during time interval $t \in T$.

Services

Departure times and frequencies are fixed and publicly available. Passengers know when the trains depart and plan their travelling accordingly. Departure times are very inflexible because time slots are negotiated with a third party (the infrastructure manager) since the network is shared with other operators. We consider the possibility that planned services may be cancelled.

A train service is a passenger train travelling from a depot station to another depot station stopping at a number of intermediate stations. Services are defined by an origin, a destination and a departure time. We consider two kinds of services: planned services are the train services that are planned according to the undisturbed scenario. The other kind of services are called failure services, these services are extra services that may be inserted to alleviate the effects of a disruption.

The planned services may be cancelled due to some incidence. This issue can be modelled through cancellation variable or reducing the arc capacity where the incidence is taking place, so the model will cancel the necessary services to satisfy the new capacities.

For failure services the model will decide whether they are used or not. We introduce the protection arcs. A protection arc represents a feasible movement between depot stations, and it is defined by a departure station, an arrival station and every intermediate arc. That is, a protection arc going from one depot to another one will pass through every station between them. We define a feasible movement as a physical movement in the network after the incidence. From this point, the model decides whether a protection arc is assigned to a departure time or not, based on the knowledge of passenger flow in each arc. We may define failure services based on arcs, but this approach leads to huge number of variables representing them, thus we define the protection arcs.

Passengers

We assume that the demand, disaggregated by market (pair origin-destination at a given period), is known data. The demand is realized by routes. A route is defined by its origin, its destination, its departure time and by the timetable services used. Every passenger is willing to travel in planned routes but due to an incidence they can go in alternative routes with an additional cost. The number of routes offered to a given demand, depending also on the active services, is extremely large, so they cannot explicitly give as data, especially considering that the actual train services are variables.

One possibility is to disaggregate by decomposition in an outer model, where the service decisions are taken, and in an inner model, where for a given service alternative the passengers realize the travel through the services. In this way, each service alternative is valued by the passenger decision (under the assumption of a centralized system or without considering explicitly the congestion).

The other possibility, more far of the actuality but more easy to implement, is to consider that we know the passenger arc flow in all the sections of the services (perhaps using historically data and inference methods); in this case, this passenger flow data will be considered in passenger constraints in flow capacity constraints that force that the vehicle flow capacity in these arcs is enough to attend the flow. This option is closer to the Rolling Stock assumptions and it is below assumed.

Passengers are represented by demand on arcs through time periods. Let TD_a represent the time periods through which demand is counted. Each period is a set of time intervals $\tau \in TD_a$. The demand on arc a during time period τ is denoted by $ff_{a,\tau}$.

MODEL FORMULATION

The mathematical formulation follows:

-Sets:
S: set of stations.

$SC \subset S$: set of depot stations.
A: set of arcs. Each arc $a \in A$ goes from departure station $ds_a \in S$ to arrival station $as_a \in S$
PA: set of protection arcs. Every protection arc $pa \in PA$ is defined by an origin depot $ds_{pa} \in SC$, a destination depot $as_{pa} \in SC$, and every intermediate arc.
$CPA_a \subset PA$: set of protection arcs containing arc a.
$DPA_s \subset PA$: set of protection arcs departing from depot s.
$APA_s \subset PA$: set of protection arcs arriving in depot s.
T: set of time intervals indexed by t.
$TS_s \subseteq T$: set of time intervals relevant for each station s, indexed by τ.
$TD_a \subseteq T$: set of time intervals at which the demand is counted in each arc a, indexed by τ.
C: set of compositions.

-Parameters:
$fc_{pa,t}$: cost of assigning protection arcs $pa \in PA$ to departure time $t \in T$
oc_c: operating cost per kilometre of composition $c \in C$.
km_{pa}: distance in kilometres of protection arc $pa \in PA$.
$km_{s,s'}$: distance in kilometres from station s to station s'.
$upc_{a,\tau}$: cost per unattended passenger in arc $a \in A$ during time interval $\tau \in TD_a$.
ic_c: investment cost for rolling stock composition $c \in C$.
$ff_{a,\tau}$: passenger flow on arc $a \in A$ during time interval $\tau \in TD_a$.
$dq_{s,\tau}$: out coming service capacity in station $s \in S$ during time interval $\tau \in TS_s$
$aq_{s,\tau}$: in coming service capacity in station $s \in S$ during time interval $\tau \in TS_s$
$q_{a,t}$: train capacity of arc $a \in A$ at time interval $t \in T$.
cap_c: passenger capacity in composition $c \in C$.
$dt_s(pa,t)$: departure time from station $s \in S$ of protection arc pa which departed from initial depot at period t.
$at_s(pa,t)$: arrival time in station $s \in S$ of protection arc pa which departed from initial depot at period t.

-Variables:
$f^c_{pa,t} \in \{0,1\}$: =1, if protection arc pa at period t is performed with composition c; 0, otherwise.
$em^c_{s,s',t} \in \{0,1\}$: =1, if empty movement between stations s, s' is performed at period t with composition c; 0, otherwise.
$dp_{a,\tau} \in Z^+$: it denotes the number of passengers in arc a that are unattended during time period $\tau \in TD_a$.
$yn_c \in Z^+$: it represents the number of rolling stock compositions c to purchase.

Objective Function

$$Min\ z = \sum_{pa\in PA}\sum_{t\in T}\sum_{c\in C} fc_{pa,t} oc_c km_{pa} f^c_{pa,t} + \sum_{s,s'\in SC}\sum_{t\in T}\sum_{c\in C} oc_c km_{s,s'} em^c_{s,s',t} + \sum_{a\in A}\sum_{\tau\in TD_a} upc_{a,\tau} dp_{a,\tau} + \sum_{c\in C} ic_c yn_c \quad (1)$$

In the objective function the following terms have been considered, every one representing an economic penalization:

1. Operating cost for train services ($f^{c}_{pa,t}$) and empty movements ($em^{c}_{s,s',t}$).

2. Cost of unattended passengers ($dp_{a,\tau}$).

3. Cost of investment in rolling stock material (yn_{c}).

Service Constraints

$$\sum_{pa\in DPA_s}\ \sum_{\substack{t\in T:\\ dt_s(pa,t)\in\tau}}\ \sum_{c\in C} f^{c}_{pa,t} \le dq_{s,\tau} \qquad \forall s\in S, \tau\in TS_s \qquad (2)$$

$$\sum_{pa\in APA_s}\ \sum_{\substack{t\in T:\\ at_s(pa,t)\in\tau}}\ \sum_{c\in C} f^{c}_{pa,t} \le aq_{s,\tau} \qquad \forall s\in S, \tau\in TS_s \qquad (3)$$

$$\sum_{pa\in CPA_a}\ \sum_{\substack{t'\in T:\\ dt_{ds_a}(pa,t')\le t\le at_{as_a}(pa,t')}}\ \sum_{c\in C} f^{c}_{pa,t'} \le q_{a,t} \qquad \forall a\in A, t\in T \qquad (4)$$

Station's departure capacity constraints (2) denote that at most $dq_{s,\tau}$ services depart from station $s\in S$ at time interval $\tau\in TS_s$. Likewise, station's arrival capacity constraints (3) ensure that at most $aq_{s,\tau}$ services arrive at station $s\in S$ in time interval $\tau\in TS_s$. In this way, the headway can be maintained.

Arc capacity constraints (4) make sure that the number of trains in each arc at any time interval is limited by the parameter.

Passenger Constraints

$$\sum_{pa\in CPA_a}\ \sum_{\substack{t\in T:\\ dt_{ds_a}(pa,t)\in\tau}}\ \sum_{c\in C} cap_c f^{c}_{pa,t} \ge ff_{a,\tau} - dp_{a,\tau} \qquad \forall a\in A, \tau\in TD_a \qquad (5)$$

Passenger capacity constraints (5) ensure that for each arc $a\in A$ and each time interval $\tau\in TD_a$, the capacity of the trains is enough to accommodate the passenger demand minus unattended passengers ($dp_{a,\tau}$).

Rolling Stock Constraints

The rolling stock constraints are different depending on the business area of the railway. We formulate the constraints divided in two groups: RENFE and NS rolling stock constraints.

RENFE rolling stock constraints are oriented to a rapid transit network in a metropolitan area. NS rolling stock constraints are oriented to a dense railway network in an interurban area.

RENFE Rolling Stock Constraints

The rolling stock for metropolitan rapid transit operator as RENFE in Madrid, Spain, consists of taking decisions about the different compositions of the trains (simple or double composition). Each one has a capacity for transporting passengers. We consider also the possibility for investing in more rolling stock. In the short term context this does not refer to the purchase of new rolling stock but rather means that extra rolling stock can be borrowed from other lines at a certain cost.

Composition Conservation Constraints ensure the convoys balance. These constraints ensure that the train number for every station and material at period $t-1$, plus the arriving trains, minus the departing ones is equal to the train number at period t.

Rotation and Departure Constraints ensure that a rotation is performed before each train service departure.

Fleet Capacity Constraints ensure that the number of trains used at any time is limited by the size of the fleet. These constraints count the running trains and those ones in depot stations. The constraints will be considered flexible, for this, the possibility to buy additional trains will be considered, but a very high price.

Trains Initial and Final Constraints denote that the numbers of compositions available at the stations at the beginning and end of the planning period are given.

The formulation about these constraints may be found in Cadarso and Marín (2010).

NS Rolling Stock Constraints

In NS, rolling stock units can be combined to form longer trains. The rolling stock units that make up a train is referred to as a composition. Due to shunting restrictions the order of the units in the composition is relevant, therefore a composition can be viewed as a string, where each element is a material type and the index represents the position in the composition.

At each depot station we keep track of the compositions parked at the platforms and the units in the depot. When a service arrives at a depot station the whole composition or a part of it is placed at the platform and the uncoupled units are added to the depot. When a service departs, part of the assigned composition is taken from the platform at the remaining units (if any) are retrieved from the depot.

Arrival Composition Constraints denote that when a service arrives at the end station with a given composition $c1$ then a composition $c2$ is put the platform of the station. Likewise, Departing Composition Constraints state that when a service departs from the start station with composition $c1$ is uses composition $c2$ from the platform of the station.

Composition Conservation Constraints denote that the number of compositions of type c at the platform of a given station and time t equals to the number in the previous time interval $t-1$ plus the number uncoupled to the platform at this time interval minus the number coupled to departing services at the same time.

Train Type Conservation Constraints denote that the number of units of a given type in the depot of a given station at time t is equals the number of units in the previous time interval $t-1$ plus the number of units uncoupled from arriving services at time t minus the number of units coupled to departing services at the same time.

Platform Capacity Constraints denote that the number of compositions at the platforms of a given station is limited by the number of available platforms.

Composition and Trains Initial and Final Constraints denote that the numbers of compositions and units available at the stations at the beginning and end of the planning period are given. The possibility for purchasing extra units can be modeled by adding purchase variables to these constraints.

Many of the mentioned constraints can be found in Maróti (2006).

COMPUTATIONAL EXPERIENCE

We present some computational experience for realistic cases drawn from RENFE's regional network in Madrid, also known as "Cercanías Madrid" (Figure 1). This network is composed of more than 10 different lines with near 100 stations. All data are from year 2008.

Our runs have been performed on a Personal Computer with an Intel Core2 Quad Q9950 CPU at 2.83 GHz and 8 GB of RAM, running under Windows Vista 64Bit, and our programs have been implemented in GAMS/Cplex 11.1.

We have considered an incidence blocking an arc in both senses for all the day in the line C5. This line can be considered as an independent line for rolling stock assignment purposes. However, it shares some stations with line C4. In this way the demand attempting to use the broken arc may be redirected through these alternative lines. We can see in Figure 2 the network topology after the incidence has begun. In yellow color the C5 depot stations are shown, in blue color the C4 depot stations and in purple color the C3 depot stations. In red color shared stations are shown.

Figure 1 – RENFE's regional network in Madrid

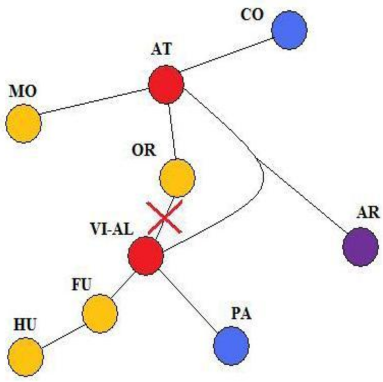

Figure 2 – RENFE's regional network after the incidence

As we can see in Figure 2 line C5 is fully broken. Then, protection arcs must be defined. These protection arcs are designed attending to demand purposes. In this study case the chosen protection arcs are shown in Table 1.

Table 1 – Protection arcs in line C5

Protection arc	Origin	Destination
pa1	MO	AT
pa2	AT	OR
pa3	VI-AL	FU
pa4	FU	HU
pa5	HU	FU
pa6	FU	VI-AL
pa7	OR	AT
pa8	AT	MO
pa9	MO	OR
pa10	OR	MO

The model assigns departure times to protection arcs defined above. In Table 2 line C5 operating costs are summarized. The first case refers to a planned situation and the second case to the incidence case. In the second column train service operating costs (TSOC) are shown; in the incidence case they are lower than in the planned case because due to the incidence no complete service can be performed. In the third column empty movement operating costs (EMOC) are summarized. In the fourth column passengers in excess costs (PEC) are written; this cost refers to a situation when passengers are going in an uncomfortable way; in the incidence case this cost is lower because the incidence mandates a lot of passengers to change their trip. Finally, in the last column, composition changes (CC) are addressed; there are no composition changes in the incidence case favouring the system recoverability.

Table 2 – Costs in line C5

Case	TSOC	EMOC	PEC	CC
Planned	80099.7	1292.64	3554	20
Incidence	57979.84	1923.04	1441	0

As mentioned above we will suppose that the demand disrupted due to the incidence is fully redirected to line C4. Under this assumption we are in the worst case, where all the demand is absorbed by the network. However, in a realistic case part of the demand would choose another mode of transportation.

In this way, the rolling stock assignment must be rescheduled in order to attend the extra-demand. However, the timetable in line C4 will be maintained in order to avoid the incidence propagation. In order to compare both situations the planned one and the incidence response, in Table 3 line C4 costs are shown. In the second column train service operating costs (TSOC) are shown; for the incidence case they are slightly bigger because more rolling stock must be rolled in order to attend the demand. In a similar way, empty movements operating costs (EMOC) are shown in the third column. An important cost is the passengers in excess cost (PEC), which is greatly incremented for the incidence case. Finally, in the last column composition changes (CC) are shown; this number also grows for the incidence case.

Table 3 – Costs in line C4

Case	TSOC	EMOC	PEC	CC
Planned	87837.52	4090.83	2177	34
Incidence	94103.14	6683.91	33747.50	42

CONCLUSIONS

A mathematical formulation has been proposed to address the recoverability of railway transport system. This formulation has been developed based on previous works in both NS in Holland and RENFE in Spain transportation systems.

The results are satisfactory because, in addition to the commercial train services, they also account for the empty movements, the adequate allocation of the material in the depots, the optimal convoy mix to form the trains, and the rotation times.

A computational experience based on RENFE network has been presented. The results have been positively received by network operators.

Future research may include the model adaptation for other and more complicated incidences.

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