Disruption Management in Passenger Transportation - from Air to Tracks

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Abstract. Over the last 10 years there has been a tremendous growth in air transportation of passengers. Both airports and airspace are close to saturation with respect to capacity, leading to delays caused by disruptions. At the same time the amount of vehicular traffic around and in all larger cities of the world has show a dramatic increase as well. Public transportation by e.g. rail has come into focus, and hence also the service level provided by suppliers ad public transportation. These transportation systems are likewise very vulnerable to disruptions.

In the airline industry there is a long tradition for using advanced mathematical models as the basis for planning of resources as aircraft and crew. These methods are now also coming to use in the process of handling disruptions, and robustness of plans has received much interest. Commercial IT-systems supplying decision support for recovery of disrupted operations are becoming available. The use of advanced planning and recovery methods in the railway industry currently gains momentum.

The current paper gives a short overview over the methods used for planning and disruption management in the airline industry. The situation regarding railway optimization is then described and discussed. The issue of robustness of timetables and plans for rolling stock and crew is also addressed.

1 Introduction

1.1 Background

Over the last 10 years there has been a tremendous growth in air transportation of passengers. This has lead to a situation, where both airports and airspace are close to saturation with respect to capacity. As a consequence delays constitute an ever-increasing problem for all major airlines. Delays are caused by irregularities and events. Generally, a disrupted situation - often just denoted a disruption - is a state during the execution of the current operation, where the deviation from the plan is sufficiently large to render the plan infeasible, thereby necessitating re-planning. Note that a disruption is not necessarily the result of one particular event.

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At the same time the amount of vehicular traffic around and in all larger cities of the world has also dramatically increased, and the time lost daily by each individual in traffic queues is now counted in hours. Therefore public transportation has come into focus, and hence also the service level provided by suppliers of public transportation. One key element here is punctuality. However, also these transportation systems are very vulnerable to disruptions decreasing the system capacity.

In the airline industry there is a long tradition for using advanced mathematical models as the basis for planning of resources as aircraft and crew, cf. [1, 2]. In the recent years these methods have also found their way into the process of handling disruptions. Robustness of plans, which may be interpreted as pro-active disruption management, has received much interest. Commercial IT-systems supplying decision support for recovery of disrupted operations are becoming available.

A number of features in the planning processes are similar in air and railway transportation. Operating public railway transportation systems are nevertheless complicated by the mere size of the operation, by additional constraints regarding the use of rolling stock and crew, but also by the larger set of possible actions in a disrupted situation and by the interaction between these.

Therefore, the use of advanced planning methods in the railway industry has taken momentum a decade later than in the airline industry. A good overview is given by [3]. The use of such methods to recover after disruptions is, however, in its infancy.

1.2 Contribution

The current paper aims at enhancing the understanding and knowledge of the optimization methods applicable in disruption management as well as the difficulties faced when applications are to be introduced in real-world applications. Since the methods are intimately related both to the planning processes prior to the operation and to the operational context for the operation itself, both of these issues are addressed in some detail. The reader is assumed to have general knowledge of operations research and mathematical programming, but no special knowledge about applications in air and railway transportation.

1.3 Outline of Paper

We first describe the operational context, the planning process and the techniques used for each of the individual resources in the airline case. Then we describe the results of current research effort regarding disruption management and robustness. The next part of the paper deals with passenger transportation in the railway industry addressing basically the same issues to reveal similarities and differences. We focus on mass passenger transportations as seen in densely populated areas and major cities, using the activities of the company DSB S-tog as examples. Finally, we comment on the perspectives of ongoing and future development in the railway sector for disruption management based on decision support systems .

2 The Airline Industry

2.1 The Operational Context for Airlines

All airlines share the common resources of airspace and airport capacity. Hence airlines cannot independently determine their preferred schedule and plans for aircraft and crew, and in a disrupted situation airlines in general have to collaborate with aviation authorities regarding recovery possibilities. Institutions like the Federal Aviation Authorities (FAA) in the United States and EUROCONTROL have the responsibility to balance the use of the scarce resources through restricting schedules and through air traffic flow management (ATFM). If a disrupted situation stems from decreased airport capacity due to e.g. weather conditions it is likely that all operating airlines are affected. Hence, the decision process has a number of stake-holders, and the information flow in the recovery process becomes very important. For a more detailed description, see [1].

2.2 The Planning Process

The following section is based on [2]. In general, the planning process for passenger transportation is sequential, and this holds also for airline operations. Based on forecasts of passenger demand, available slots at the airports, and other relevant information, a timetable in terms of a flight schedule is constructed. Fleet assignment then determines which specific type of aircraft is assigned to each flight, and at the same time lines of work - rotations - for physical flights are determined. In the crewing phase cockpit crew and cabin crew are assigned to all flights. For both crew groups, individual flights are grouped to form pairings. Each pairing starts and ends at the same crew base. These pairings are at this point anonymous. Pairings are then grouped to form personnel rosters, and rosters are assigned to crew - usually based on seniority. Rosters are typically lines of work for 14 days or one month. Finally, physical aircraft from a given fleet are assigned to flights in the tail assignment process.

In the planning process a number of issues have to be dealt with as e.g. aircraft maintenance rules, and regulations for crew on flying time and off-time based on international and national rules, and on agreements with unions. The tracking phase - sometimes referred to as short-term planning - handles changes in plans due to e.g. crew sickness, aircraft breakdowns, and changes in passenger forecasts.

The responsibility for all plans is transferred to the operations control center (OCC) a few days days ahead of the day of operation. It is the responsibility of OCC to ensure availability of all resources so that the flight plan seen as an integrated entity is feasible. Events like crew sickness and late flight arrivals have to be handled, and not only the immediately affected flights but also knock-on effects on other parts of the schedule must be considered.

2.3 Network Models for Airline Optimization Problems

Two networks models are dominant in connection with airline and railway optimization: connection networks and time-line networks. We describe these networks in the following since such networks are often used in recovery methods. A more detailed presentation is given in [2].

The connection network or time-space network is used to represent the possibilities for building rosters for aircraft and crew. The network is an Activity-On-Node network. It consists of a set of nodes, N, one for each flight leg. A flight leg is given by its origin, destination, departure time and date, and arrival time and date. The node i representing the flight leg l_i is connected by a directed edge (i, j) to the node j representing the flight leg l_j if it is feasible with respect to turn-around-times and airport to fly l_j immediately after l_i using the same aircraft/crew. In addition, there are nodes indicating the position of each aircraft/crew both at the beginning and in the end of the planning horizon. These nodes are connected to those leg nodes which are feasible as first resp. last legs in the planning period. A path in the network now corresponds to a sequence of flights feasible as part of a rotation. Schedule information is not represented explicitly in the network, but used when building this. Maintenance restrictions are incorporated through the concept of a maintenance feasible path, which is a path providing sufficient extra time with the required intervals at a node for a station, where maintenance can take place. Note that the number of feasible paths is very large - it grows exponentially with the planning time horizon.

In connection networks it is difficult to see the representation of the possible schedules. Time-line networks represent the possible schedules in a natural way. A time-line network has a node for each event - arrival and departure. Each station has a time line with event-nodes located at the relevant points in time. The edges of the network connect event-nodes corresponding to events that may follow each other in a sequence of events for the resource in question. An edge for a particular flight goes between the departure and the arrival station.

Below we briefly describe a model for aircraft rotations based on connection networks.

2.4 Aircraft Rotation Based on Connection Networks

The model based on connection networks described below can be found in [4] by Cordeau, Stojkoviċ, Soumis, and Desrosiers. Assume that particular fleet has been assigned to each flight, and consider the problem of assigning aircraft to flights over a fixed time horizon while respecting maintenance requirements.

The set of available aircraft is called F, and for each aircraft $f \in F$, an origin o^f and a destination d^f is given. The set of nodes $N^f = N \cup \{o^f, d^f\}$ consists of the flights, the origins and destinations. There are edges from each origin node to flights feasible as first flights for an aircraft located at the origin node, and edges into destination nodes from flights feasible as last flights with respect to the origin. Furthermore, the set Ω^f denotes the set of feasible paths between o^f and o^d in the network. Only maintenance feasible paths are considered. The relations between the flights and the paths are given by binary parameters a^i_ω taking the value one iff flight i is on path ω.

Define now binary decision variables x_ω taking the value one iff the flights on the path given by ω is flown by the aircraft determined by the origin node of the path. The constraints of the problem are that each flight must be in one of the selected paths, and that one path must be chosen for each aircraft. The routing problem becomes:

$$\begin{array}{lll}
\text{minimize} & \sum_{f \in F} \sum_{\omega \in \Omega^f} c_\omega x_\omega & \\
\text{subject to} & \sum_{f \in F} \sum_{\omega \in \Omega^f} a^i_\omega x_\omega = 1 & i \in N \\
& \sum_{\omega \in \Omega^f} x_\omega = 1 & f \in F \\
& x_\omega \in \{0, 1\} & f \in F; \omega \in \Omega^f
\end{array}$$

An immediate solution approach is Branch-and-Price, i.e. LP-based Branch-and-Bound combined with column generation, where each column represents a feasible path.

2.5 Disruption Management

To produce recovery plans is a complex task since many resources (crew, aircraft, passengers, slots, catering, cargo etc.) have to be re-planned in close-to real-time. A disruption is in most cases addressed by solving the problem in a sequential fashion with respect to the components: aircraft, crew, ground operations, and passengers. Infeasibilities regarding aircraft are first resolved, then crewing problems are addressed, ground problems like stands etc. are tackled, and finally the impact on passengers is evaluated. Sometimes, the process is iterated with all stake-holders until a feasible plan for recovery is found and can be implemented. In most airlines, the controllers performing the recovery have only limited IT-based decision support to help construct high-quality recovery options. The controllers are often content with producing a single viable plan of action, as it is a time consuming and complex task to build a recovery plan. Furthermore the controllers have little help in estimating the quality of the recovery action they are about to implement.

The most commonly used recovery options are:

- **Using standby resources:** Airlines usually have staff members on stand-by duties at bases, and sometimes also stand-by aircraft are available.
- **Deadheading of resources:** Crew or aircraft located in one station are moved to another in order to relieve a disrupted situation here. Deadheading is usually costly.
- **Swapping of tasks:** Tasks of two resources (crew or aircraft) may be swapped if the second one is available for taking over the task of the first one, which then continues the tasks for the second. A chain of swaps may be necessary to recover.

- **Re-timing:** A planned departure is delayed. In general there are knock-on effects using re-timing as recovery tool.
- **Cancellation:** Canceling one or several departures is usually used as the last opportunity - it is considered unacceptable from a customer point of view and is hence avoided if possible.

Companies often work with preferred recovery strategies, and it is important to be able to evaluate such a strategy. This requires knowledge of possible disruption patterns in terms of frequency and distribution over time. Furthermore it is necessary to be able to simulate the complete operation when the strategy in question is applied to alleviate disruptions. Simulation is the most common way to approach this problem, and in air transportation several software tools are available for this, e.g. SimAir [5].

Determining the quality of a single recovery option is also difficult. The objective function is composed of several conflicting and sometimes non-quantifiable goals as e.g. minimizing the number of passenger delay minutes, returning to the plan as quickly as possible, and at the same time minimizing the cost of the recovery operation.

An important parameter for disruption management is the time window for the disruption. A recent prototypical recovery approach is to fix all activities outside the time window, and then re-plan for the affected resources within the time window. In the re-planning process, connection networks are constructed from the modified flight schedule for aircraft and for crew and then used to generate feasible lines of work and duties. These are then used as input for the planning software, which due to the much smaller problem size is able to produce new plans in a sufficiently short amount of time. Other approaches are to use tailored software for disruption management often based on multi commodity network flow models. Table 1 indicates the development in aircraft recovery methods over the last decade, whereas Table 2 indicates the corresponding development for crew.

2.6 Pro-active Disruption Management - Robustness

Robustness of plans as a means of avoiding disruptions has attracted an increasing interest over the last years. [1] contains an interesting section describing a number of robustness ideas, which have all been addressed by researchers lately, among others:

- **Allocation of slack:** Slack is extra time in connection with e.g. turnarounds allocated such that small delays do not propagate. The challenge is to balance the amount of slack against the cost of the slack, and to distribute the available slack time in the optimal way over rotations and rosters.
- **Minimizing expected crew costs:** In deterministic models the planned crew cost is fixed. Taking into account expected cost from recovery, e.g. by using techniques from stochastic programming, leads to plans balancing the cost of an undisrupted operation against the cost of recovering from a disruption.

		Functionality				Dimensions				
Authors	Model	Canx	Retim	Fleets	Data	AC	Fleets	Flights	Solution time	Obj.
Teodorovic, Guberinic	CN	No	Yes	No	G	3	1	8	NA	DM
Teodorovic, Stojković	CN	Yes	Yes	No	G	14	1	80	180	C, DM
Teodorovic, Stojković	CN	Yes	Yes	No	G	NA	1	80	140	C, DM
Jarrah, Yu, Krishnamurthy, Rakshit	TLN	Yes	Yes	No	RL	NA	9	NA	0-30	D, S, F
Mathaisel	TLN	Yes	Yes	No	NA	NA	NA	NA	NA	DF
Talluri	CN	No	No	Yes	G	NA	NA	NA	10	Sw
Argüello, Yu, Bard	–	Yes	Yes	Yes	RL	16	1	42	2	C
Clarke	CN	Yes	Yes	Yes	RL	177	4	612	NA	CR
Yan, Lin	TLN	Yes	Yes	No	RL	17	1	39	49	CR
Yan, Tu	TLN	Yes	Yes	yes	RL	273	3	3	1800	CR
Cao, Kanafani	TLN	Yes	Yes	No	G	162	1	504	869	RC
Lou, Yu	NA	No	Yes	NA	RL	NA	NA	71	15	DF
Lou, Yu	NA	No	Yes	NA	RL	NA	NA	71	15	DF
Løve, Sørensen	TL	Yes	Yes	No	RL	80	1	340	6	RC
Thengvall, Bard, Yu	TLN	Yes	Yes	No	RL	27	1	162	6	RC
Thengvall, Yu, Bard	TLN	Yes	Yes	Yes	RL	332	12	2921	1490	RC
Bard, Yu, Argüello	TBN	Yes	Yes	No	RL	27	1	162	750	DC
Andersson	CN	Yes	Yes	Yes	RL	30	5	215	10-1100^1	R
Rosenberger, Johnson, Nemhauser	NA	Yes	Yes	No	G	96	1	407	16	C, R

Table 1. Summary of published experiments regarding aircraft recovery. The model is either a connection network (CN), a time line network (TLN), or a time band network (TBN). Data are either generated (G) or real-life (RL) instances. Solution times are in seconds. Fleets indicate whether multiple fleets can be dealt with concurrently. The objectives to minimize are cancellations (C), delay minutes (DM), delay (D), number of swaps (Sw), number of delayed flights (DF), cost minus revenue (CR). Maximize revenue minus cost (RC) is also used. The table is from [2].

		Functionality				Dimensions		Sol.	
Authors	Model	Canx	Retiming	Indv. Rost.	Data	Crew	Flights	time	Obj.
Stojković, Soumis, Desrosiers	TLN	No	Yes	Yes	RL	NA	210	1200	PC
Wei, Yu, Song	STN	No	Yes	No	NA	18	51	6	RC
Lettovsky, Johnson, Nemhauser	TLN	Yes	(Yes)	No	RL	38	1296	115	PC
Medard, Sawhney	TLN	NA	Yes	Yes	NA	885	NA	840	L
Abdelgahny et al.	NA	No	Yes	Yes	RL	121	NA	2	D, St, Sw

Table 2. Summary of papers regarding aircraft recovery. TLN is Time Line Network, STN is Space Time Network, and RL is Real-life. Solution times are in seconds. Objectives are pairing costs (PC), Return to schedule (RS), Legality (L), Deadhead, Stand-by (St), and Swap (Sw). The table is from [2].

- **Ensuring crew swap possibilities:** Since swapping of crew is a well-known recovery action, one way of ensuring some degree of robustness is to construct the original plan using a cost function, which favors plans with swap possibilities.

Note that the examples above reveal that robustness of plans comes in two types: One aiming at producing a plan which is less vulnerable to disruptions, and one aiming at easy recovery in case of disruption.

No general framework to deal with robustness as a concept, and no general properties ensuring robustness have been put forward. Simulation is as mentioned an important tool in investigating the interplay between plans and recovery actions and is also indispensable when evaluating robustness.

3 The Mass Transportation Railway Industry

Railway systems in densely populated areas are very vulnerable to disruptions in the operation. The timetables are usually tight and trains run with a high frequency to satisfy customer requirements. A sequence of small delays caused by passenger related events rapidly accumulates a delay so substantial that knock-on effects on other parts of the operations results.

To illustrate the situation we show three tables from [6]. The first reports the numbers of disruptions related to infrastructure in the Netherlands during the first half of 2006.

Similar information from DSB S-tog is shown in Tables 4 and 5. Note the substantial number of disruptions caused by the infrastructure manager and the passengers. In the next section we describe the operational context of the operation for a train operator and the role of the infrastructure manager.

Class	Disruptions	Avg. duration	Total duration
Technical failure	1656	2.2	3680
Third parties	1471	1.0	1491
Weather	172	2.3	393
Others	693	1.7	1208
Total	3992	1.7	6772

Table 3. Disruptions in the Netherlands related to infrastructure during the first half of 2006

Responsible	Infrastructure manager	S-tog	Externally caused
Affected trains	4746	3981	660

Table 4. Disruptions in the S-tog traffic for an average month in 2006 subdivided according to responsibility.

3.1 Operational Context for Train Operators

A daily passenger transportation operation involving several train operators involves the same type of actors as for air transportation: Parties responsible for safety and for coordination of the operations of the different operators, and the planning and dispatching divisions of each operator. However, here the infrastructure used for the physical transportation is tracks and signals, i.e. physical entities. The infrastructure is often owned by a public entity, and the responsibility lies with an infrastructure manager. The infra structure owner maintains signals and tracks, and ensures that timetables of the different operators are feasible from an over-all point of view. Signals and tracks are often the cause of disruptions.

In connection with disruptions and recovery, the major tasks to be carried out are timetable adjustment, rolling stock re-scheduling, and crew re-scheduling. Figure 1 from [6] shows how the responsibilities for the different elements are shared among the actors.

The infrastructure manager controls and monitors all train movements in the railway network. The Network Traffic Control (NTC) covers all tasks corresponding to the synchronization of the timetables of the different operators. NTC has to manage overtaking, re-routing, short turning, or canceling trains in order to prevent them from queuing up. The latter is a permanent threat at the basically one-dimensional railway infrastructure. Queuing up of trains immediately leads to extensions of travel times.

Responsible	Rol. St.	Drivers	Dispatch.	Maint.	Passengers	Misc.
Affected trains	1131	665	88	44	1737	316

Table 5. Disruptions contributed to S-tog for an average month in 2006 (in total 3981) subdivided according to cause.

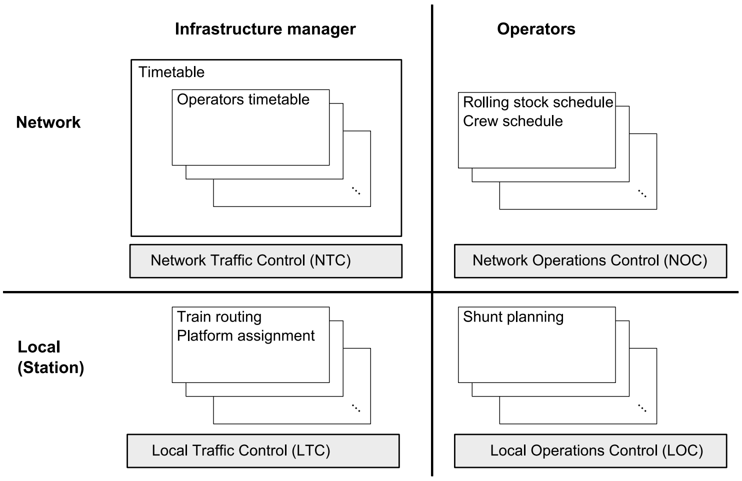

Fig. 1. Schematic view of actors, timetables and resource schedules

On a local level, the process is managed by the Local Traffic Control (LTC). For example, LTC is responsible for routing trains through railway stations and for platform assignments. Safety is normally ensured by headways and automatic track occupancy detection systems.

3.2 The Planning Process

The planning process for railway operators is very similar to the one described for airline transportation. First comes line planning determining the network of lines to be serviced, then follows timetabling, rolling stock planning, and finally crew scheduling. The complete process is usually sequential and extends over several months. We refer to [3], which describes the process in some detail.

3.3 S-tog - the Company, Network, Resources, and Operational Conditions

In the following we often refer to DSB S-tog a/s (S-tog) for illustrative purposes. The description is a short version of the one given in [7], where additional details can be found.

DSB S-tog is the major supplier of rail traffic on the infrastructure of the city-rail network in Copenhagen. S-tog has the responsibility of buying and maintaining trains, ensuring the availability of qualified crew, and setting up plans for departures and arrivals, rolling stock, crew etc. The infrastructural responsibility and the responsibility of safety for the S-tog network lie with Banedanmark, which is a company owning the major part of the rail infrastructures in Denmark.

The S-tog network consists of 170 km double tracks and 80 stations. The network consists of two main segments. The circular rail runs from Hellerup in the north to Ny Ellebjerg in the south. The remaining network consists of seven segments: Six fingers and a central segment combining the fingers. The network, shown in Figure 2, is serviced by a number of lines. These all pass the central segment, which includes Copenhagen Central (København H).

Most lines in the network are run according to a cyclic timetable and have a frequency of 10 minutes. On the outer parts of one finger this frequency is reduced to 20 minutes, but the assignment of fingers to lines ensures that almost all stations are serviced by 6 trains per hour. There are at daily level appr. 1200 departures from end stations, and additionally approximately 28.000 departures from intermediate stations.

S-tog currently has 104 so-called ”1/1-units” each seating 336 passengers, and 31 ”1/2-units” seating 150. The units can be combined to various train sizes allowing for more flexible composition of trains. The company employs approximately 550 drivers. At the most busy time of day the network presently requires 86 1/1-units and 27 1/2-units to cover all lines and departures, including standby units (2 1/1-units and 1 1/2-unit).

The passengers of S-tog travel on different types of tickets and cards valid for all public transportation according to a zone system in the Greater Copenhagen area. Tickets are currently not inspected when passengers board or leave trains. Instead, spot inspections are performed by ticket inspectors.

The quality of the service provided by S-tog is measured by two performance indicators: Punctuality and reliability. Punctuality focuses on the number of trains arriving ”on time” (interpreted ”not later than 2.5 minutes after planned arrival time”), whereas reliability measures the percentage of trains actually run (i.e. not canceled) according to the schedule. The average punctuality must be at least 95 % and the average reliability 97.5 % according to the contract between S-tog and the Ministry of Transportation. This contact also sets lower bounds on the number of trains kilometers run over a time period, and establishes service levels in terms of seat availability compared with the expected number of passengers on departures.

The planning processes of S-tog regarding timetabling, rolling stock planning, and crew scheduling are described in detail in [7].

The trains in the timetable of S-tog are of two types: Fast trains and stop trains. Accommodating both types of trains in a timetable can only be achieved at the expense of service: Even though all stations are serviced with two trains every 20 minutes, some stations may be served regularly every 10 minutes whereas other may have up to 18 minutes between the two trains. This mixture of fast and stop trains also present challenges in case of disruptions.

Rolling stock operational conditions are intimately related to the trade-off between service level and cost. The seat capacity provided must be large enough to accommodate the maximum number of passenger on each particular departure, but running with excess capacity is costly. Changes in the composition of trains normally happens four times a day: two changes to increase seat capacity before the two rush hours, and two to reduce seat capacity. These changes are carried out at the rolling stock depots. The depots are in general located at the

Fig. 2. The 2007 S-tog network.

terminal stations of the network, but a large depot is also located at Copenhagen Central. The depots at the terminal stations are of varying size, which implies additional constraints regarding the feasibility of rolling stock circulations when compositions are changed.

Recently, S-tog has decided to introduce planning software based on optimization methods for building the rotations for train units, and a system development process to produce optimization software capable of performing rolling stock planning is hence in progress.

S-tog employs approximately 550 drivers. The daily schedule of a driver is a so-called duty, which has to comply with a number of rules originating in safety regulations and union agreements. Such a duty is either a pre-planned sequence of driving tasks or a stand-by duty. The duties are organized in rosters. A roster is a set of week-plans for an even set of weeks, and is covered by a corresponding number of drivers in a rolling fashion. Also rosters must comply with complicated rules and regulations. Of the 550 drivers, 350 are assigned to pre-planned rosters and 200 are stand-by drivers.

To make efficient use of the driver resources, driving tasks are combined to efficient duties, and duties are then combined to efficient rosters. Efficient in this context means that the number of hours in each duty spent in the driver seat of a train must be as large as possible. S-tog uses the system TURNI [8] and PDS (a tailored version of CREWS [9]. From an operational point of view, very efficient duties and rosters on the other hand contain little slack and plans based on these are hence very sensitive to disruptions in the daily operation. Again, the trade-off between cost and robustness of a plan is apparent.

3.4 Disruption Management

In the following we describe disruption management in general using the current operation of DSB S-tog as an illustrative case.

As indicated previously and described in detail in [6], the infrastructure manager through the NTC usually has the responsibility and final decision in all issues dealing with changes in the timetable. In situations with disruptions this leads to a situation with one party deciding the actions to be taken while another party is responsible for implementing the action. Even though the staff at NTC communicates intensively with dispatchers, this division of responsibilities inevitably lead to tensions.

Generally, the handling of disruptions are based on a set of experienced dispatchers for crew and rolling stock. One central issue here is the available amount of IT support. For example, the dispatchers at S-tog have IT-support in terms of access to drivers duties and overview information regarding the status of the operation (e.g. current delays of trains in the network). However, there is often no integration between the different information systems, and there is no decision support to change driver duties.

Note that special care has to be taken regarding the rolling stock under a severe disruption due to the one-dimensional infrastructure. If one part of the network is blocked, this may have severe effects on the availability of rolling stock in other parts. Consider e.g. a closed tracks in the central section of the S-tog network. If action is not taken immediately, trains start to queue up. The first consequence is that passengers on the affected lines have no connections out of Copenhagen. The knock-on effect is that after a short while, no trains return to the outer parts of the network resulting cancellations on a large scale.

As for airlines, a number of strategies for disruption management is available. At S-tog the following options are those most commonly considered, cf. [10]:

- **Trains skipping stations i.e. making fast-trains out of stop-trains:** This option is obviously inadequate passenger forced to change trains, but it has little additional cost.
- **Reducing headways to a minimum:** In the outer ends of the network there are some slack on the headways. In the case of delays headways are reduced making the trains drive closer to each other. As the frequency of trains in the central section is high there is less slack here for decreasing headways. The option has marginal cost.
- **Reducing running times to a minimum:** Timetables are constructed given predefined running times between all sets of adjacent stations. The running time is always the minimum running time plus some slack. In case of a disruption, running times between all stations are reduced to a minimum given the particular context. The cost is marginal.
- **Shortening the routes of trains** A train can be "turned around" before reaching its terminal i.e. the remainder of the stations on its route can be skipped. Again the cost is marginal.
- **Swapping the tasks/routes of fast-trains catching up with stop-trains:** Delays some times occur so that fast lines catch up with slow lines leading to a delay of the fast trains. Here, it is possible do a "virtual overtaking", i.e. to swap the identity of the two trains so that the slow train is changed to a fast train and vice versa. This option affects the duty of the driver and the rotation of the involved train units and hence requires re-planning.
- **Allowing overtaking on stations with available tracks:** Handling the daily operation is in general less complex if there is a predetermined order of train lines. In the case of a disruption the predetermined order of lines can be broken on stations with several available platforms in the same direction i.e. where overtaking between trains is possible. Here, re-planning must take place.
- **Inserting replacement trains from Copenhagen Central for trains that are delayed:** If a train is delayed in the first part of its route, it is often replaced by another train departing on-time. This requires a stand-by train unit and a driver to do the necessary shunting. Again, duties and rotations are affected.
- **Canceling of entire train lines:** In the case of severe disruption entire lines are taken out, i.e. all trains currently servicing the departures on the relevant lines are taken out of operation. In the case of severe weather conditions such as heavy snow, the decision is taken prior to the start of the operation. This

option heavily influences the operation since train units are now misplaced and drivers knocked out of their duties. Recovering from this action is by no means trivial.

Each disruption management strategy has to be supplemented with methods for recovery of duties and rolling stock circulations. Some recovery methods are simple and nearly cost-less, whereas others require substantial re-planning, both for the operational day and for day succeeding this. In particular, the rolling stock circulations become affected, and in the end of the day trains units end up in depots different from the planned ones. If a misplaced unit is planned for maintenance this represent a problem not only because maintenance cannot take place, but also because maintenance is planned for particular units with respect to activities and spare parts. Thus maintenance plans may also have to be changed.

Recovery strategies in connection with rolling stock re-scheduling are often rather simple. Initially, stand-by units are exploited. These are scarce resources, so severe disruptions cannot be alleviated in this way. Other means include re-allocation of rolling stock units between trains to allow for a complete operation with respect to departures, since customers usually prefer trains with reduced seat capacity over trains canceled trains. When a disrupted situation is alleviated through the cancellation of train lines, all trains on the line have to be reinserted from the depots where they have been parked during the disruption. Here, a decision support system is in use at S-tog, which allows dispatchers to choose the optimal re-insertion time for the trains, cf. [11]

Regarding crew, the crew recovery problem at S-tog is very similar to the operational planning problem. Hence, the standard version of TURNI also has been tested for dispatching using the time window approach. All duties in the time window are re-planned, all others are left unchanged. Preliminary test with the system shows that approximately 20 minutes is required for a useful solution to be found. By relaxing some of the rules applying in a non-disrupted situation, and by efficiency tailoring, it seems likely that such an approach may become operational in a few years.

A prototype decision support system for train driver dispatchers is currently under development as a part of a Ph.D.-project supported by S-tog. The solution method to the Train Driver Recovery Problem, described in [12], is again based on rescheduling a small part of the train driver schedule affected by a disruption. The problem is formulated as a Set Partitioning problem and possesses strong integer properties. Due to that new duties are to be assigned to drivers, the problem contains generalized upper bound constraints, which implies that often the solution of the LP-relaxation is integral. The chosen solution approach is therefore an LP-based Branch & Bound algorithm.The LP-relaxation of the problem is solved with a dynamic column and constraint generation algorithm. Pilot experiments are very promising, both with regards to the integrality property and to the efficiency of the method. Solutions to the LP-relaxation for problem instances formulated over 3-5 hours of the schedule are solved within 1 second.

The largest problem instance, formulated for 8 hours of the schedule, is resolved within 46 seconds. Nearly all test instances produce integer solutions.

The main objective for the prototype is to minimize the number of changed duties to avoid the communication problem resulting from a large number of duty changes, since the communication currently is performed manually by the crew dispatcher. A second objective is to produce a robust plan, where robustness is defined as large buffer times before breaks within the recovered duties. The main focus in the project is the cancellations of entire train lines for a period of time, which is commonly used to alleviate larger disruptions.

4 Robustness

Robustness can be present in a plan in two ways. A plan is robust if disruptions can be absorbed or the resulting knock-on effects can be reduced. This type of robustness is for the complete operation usually aimed at minor disruptions and achieved through building buffer time into the plans. A plan may also be called robust if it is well suited for recovery in case of disruptions.

Absorption robustness has been studied in e.g. [13], where stochastic programming is used to distribute running time supplements in a timetable to minimize the expected delay of passenger. Recovery robustness has not been systematically addressed though its is an implicit goal in several research papers on disruption management.

A central issue from the planning point of view is the concept of pricing of robustness. Costs of plans are calculated based on figures and estimates, which are usually not easy to extract. The key question is now to assess the difference in cost between an optimal plan and a proposed robust plan. Both costs may be evaluated in undisrupted operation, but is also necessary to evaluate the cost in case of a disrupted situation. Here simulation seems to be a necessary tool.

As is the case for the airline industry, simulation tools has been developed and used for evaluating robustness of both timetables and plans. However, these tools are in general in-house products of the different operators and infrastructure managers. No general tool similar to SimAir has been developed. Such a tool would indeed be a valuable contribution to the study and development of robust planning methods.

5 Comparing Air and Tracks

In many ways disruption management for passenger transportation is similar in airlines and in railway companies.

The general structure of the operation, the planning processes, and the processes in connection with disruption management are similar. Planning tools build on the same type of mathematical models: Network representations of feasible structures as e.g. rolling stock rotations and crew rosters, and integer programming models for optimizing the plans. The models are almost always Set

Partitioning or Set Covering models, often supplied with additional constraints. The networks are used for generative purposes in the solution methods, which in most cases are of the Branch-and-Bound/Price/Cut type. One indication hereof is that software vendors for air transportation planning are major players also on market for railway planning software.

Major differences do nevertheless exist. First of all, the complexity regarding size of operation increases several orders of magnitude when moving from air to tracks. The infrastructure is one-dimensional, and there are major differences from country to country. The operation in case of mass transportation has a much larger volume with respect to passengers, and the individual traveling times are usually much shorter. Traveling usually does not require reservations, and alternative routes are often immediately available in case of cancellations. From the general planning point of view this does not create unsolvable problems, but in connection with disruption management and robustness, this results in additional time pressure and complications when different options are to be evaluated against each other.

6 Conclusion

Disruption management and robustness is becoming increasingly important in transportation applications. In the airline industry planning and disruption management systems based on advanced mathematical models and have been intensively used over the last decade. The methods usually build on a combination of network models and Set Partitioning/Set Covering IP-models. Solution methods are often based tailored versions of LP-based Branch-and-Bound like Branch-and-Price in combination with dynamic column generation. Robustness of schedules and plans have also attracted an increasing interest.

A similar development in the railway industry is now underway. Mathematically based methods for timetable design, rolling stock optimization, and crew scheduling are used by modern railway operators, and punctuality and reliability is coming into focus. The interest in disruption management and robustness is increasing. The physical infrastructure of railway operations in combination with the role played by the infrastructure manager, the necessary very short response time in case of disruptions, the existing non-integration of IT-system, and the general conservatism in the industry seems to slow down the introduction of advanced methods.

The major challenges in the coming years are the development of a general framework for understanding and classifying strategies and methods in disruption management, and for understanding, evaluating and pricing the robustness of plans. Also, the construction and successful real-life implementation of a first decision support systems for disruption management based on IT and mathematical optimization is a must for accelerating the acceptance of such systems in the industry.

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