# Airline Disruption Management - Perspectives, Experiences and Outlook*

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**Abstract**

Over the past decade, airlines have become more concerned with developing an optimal flight schedule, with very little slack left to accommodate for any form of variation from the optimal solution. During operation the planned schedules often have to be revised due to disruptions caused by for example severe weather, technical problems and crew sickness. Thus, the field of *Airline Disruption Management* has emerged within the past few years. The increased focus on cutting cost at the major airlines has intensified the interest in the development of new and cost efficient methods to handle airline disruptions.

The purpose of this paper is twofold. In the first part it offers an introduction to airline disruption management, provides the readers with a description of the planning processes and delivers a detailed overview of the numerous aspects of airline disruption management. In the second part we report on experiences from a large research and development project on airline disruption management. Within the project the first prototype of a multiple resource decision support system at the operations control center in a major airline, has been implemented.

## 1 Introduction

The principal resources for a passenger airline are crew and aircraft. Together with the passengers they constitute the three main aspects which must be planned and monitored to obtain operational efficiency. During the planning process crew, aircraft and passengers are typically seen as separate entities, which can be scheduled and optimized more or less

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independently. Given the timetable and fleet assignment (allocation of aircraft type to the flights) the planning processes run in parallel.

Crew scheduling consist of the problems crew pairing and crew rostering. In the crew pairing phase, anonymous pairings (trips), starting and ending at a home base, are constructed. In total the pairings must cover all positions to be covered in the flights defined by the time table. The purpose of crew rostering is to assign all pairings and possibly other activities to be assigned (e.g. stand-by duties) to named individuals. The crew scheduling must be completed several weeks before the day of operations and the resulting personalized rosters often span a time period of about one month. Later changes, i.e. due to changes in the timetable or in crew availability, are handled in the roster maintenance phase.

Tail assignment, i.e. the assignment of actual aircraft individuals (tail numbers) to flights (and consequently the routing of aircraft individuals), is typically done few days before day of operations. Revenue management, i.e. adjustment of prices and seat availability, is carried out in the entire period from the publication of the timetable to day of operations. These problems and their interdependencies are illustrated in Figure 1.

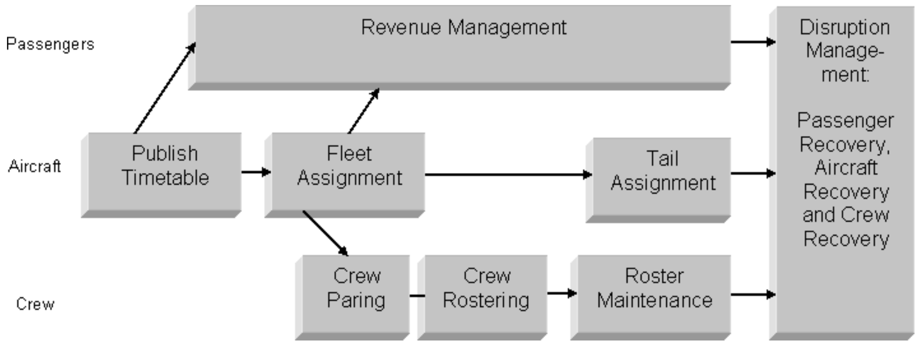


Figure 1: A simplified illustration of the scheduling of passengers, aircraft and crew in an airline.

Before day of operations the scheduling of crew, aircraft and passengers is only loosely connected. In certain cases the crew pairings or passenger connections will depend on a particular aircraft connection, i.e. that the same aircraft carry out two particular flights in sequence. This can be modelled as a "fixed link" constraint for the tail assignment and routing problem, but apart from that, there are no significant dependencies. At the day of operations, it is evident that crew, aircraft and passengers interact closely with each other in case the planned crew or aircraft schedule cannot be executed. Every change to the timetable (eg. cancellation, flight retiming, aircraft fleet type change etc.) must be feasible for crew as well as aircraft and should preferably minimize passenger inconvenience. We denote the process of monitoring and scheduling the resources close to the day of operations as *Disruption Management*. Another commonly used term to describe this problem is *operations control*.

The present paper focuses on disruption management within the airline Industry. Similar problems occur for other modes of transportation such as railways, urban transportation etc. In addition, also within production planning settings the problem of being able to recover from schedule disturbances or disruptions must be dealt with. For a more general introduction to disruption management see Clausen et al. [13].

Even though crew, aircraft and passengers by far are the most important aspects of airline disruption management, other resources must be considered as well. Examples include ground staff (check-in staff, gate staff, ramp staff, luggage staff etc), catering and gates, but these resources are generally more flexible and less expensive than crew and aircraft and will only be considered briefly in this paper.

The paper is organized as follows. Section 2 provides a survey of current airline disruption management practice. In section 3 we discuss the disruption management process and its objectives and section 4 contains a review of the academic literature on disruption management. Section 5 reports on the achievements made in the Descartes project [17] and discusses the solution methods developed for passenger, fleet and crew recovery. Furthermore, section 5 introduces ideas and basic concepts for integrated recovery. Finally, in section 6, the paper concludes on the present state of airline disruption management and gives some views on possible future developments within this area of research.

# 2 Current Airline Practice

Most commercial airlines operate according to a published schedule (time table). A schedule is typically optimized from the revenue management point of view and all airline resources should be allocated to the schedule with the least possible cost. In an ideal world, when nothing prevents an airline to operate the schedule exactly as planned, the airline will maximize its profit. In the real world, however, there are plenty of external events, which can disrupt smooth schedule execution. The most common disruptions are aircraft mechanical problems, inclement weather, airport congestion, industrial action, etc. In reaction to these events, airlines have to adjust their schedules and the corresponding resource allocation. The ability of an airline to respond to unexpected events depends on a variety of factors. In the following sections, we discuss the most important factors influencing airline operational stability and describe the current business practices of dealing with them. In section 2.1 we cover the network structure. In section 2.2 we discuss the planning and recovery strategies in use and, finally, section 2.3 describes the organization of operations control at airlines.

## 2.1 Network structure

The two most common types of route networks are point-to-point and hub-and-spoke. In the hub-and-spoke network all airports are partitioned in two sets, called hubs and spokes. Most spoke airports are served from only one hub and hubs are connected by regular flights. The vast majority of mainstream airlines operate hub-and-spoke networks, which is considered to be the most cost effective way of linking a large number of destinations. A typical passenger itinerary in the hub-and-spoke network consists of two or three legs. In order to optimise passenger connections at hubs, most North American airlines operate so-called banks, a bank is an arrival wave followed directly by a departure wave. The banks create huge peaks on demand for airport facilities, which reduces operational stability. In the aftermath of the events of September 11, 2001 and increased security checks the airlines are studying the possibility of "debanking" their operation.

Low cost airlines favour point-to-point networks. These networks directly link economically attractive pairs of destinations, providing little or no connecting possibilities. Clearly, this type of operation is less dependent on overcrowded hubs and therefore is less sensitive to major operational disruptions that are usually associated with hubs. The main remaining challenge, however, is to manage resources across the network to reduce impact of smaller disruptions, like aircraft unavailability or crew sickness.

Aircraft manufactures express their views of the future development of airline network structures in their strategic plans. So, the fortunes of the huge Airbus A380 depend on the future growth of long haul hub-and-spoke networks. On the other hand, Boeing is betting on the increasing importance of point-to-point traffic for its somewhat smaller 7E7. This also reflects differing views on how airlines will cater for the growing demand for air transport. From the passengers perspective, frequent flights with rather small aircraft is ideal but the congested airspace, limited capacity at major airports and operational costs suggest increased use of larger aircraft.

### 2.2 Resource planning and recovery strategies

During the past decade the airline industry has optimized its planning processes. Most airlines nowadays perform their key planning process, including revenue management and aircraft and crew scheduling, aided with sophisticated software tools. Although further improvements of the planning processes are possible, the focus now is seemingly shifting towards trying to ensure that the planned can be maintained through to the day of operation and can be executed smoothly in operation, i.e. that optimised resource plans are robust and allow for efficient recovery.

Usually, a disruption situation originates in a local event such as an aircraft maintenance problem, a flight delay, or an airport closure. Ideally, most disruptions should also be resolved locally using only resources directly affected by the event and within the timeframe of the event itself. In reality, disruptions tend to extend far beyond the events that originated them. For example, a small delay in the morning may trigger a cancellation in the evening. How does this happen? Part of the answer is that the resource plans tend to be optimized to a degree where no slack is available to accommodate for even a small unexpected event. Therefore even a small event can trigger a significant disruption in the airline schedule.

Clearly, all airlines try to anticipate the unexpected and to build some flexibility into their schedules. This flexibility can be used in recovering from unexpected events. The most commonly used techniques include:

- **Add Slack in the plans:** For each AC and crew rules state a minimum turn time. Instead of operating all day at a minimum turn time slack is incorporated into the plans such that each line of work has some degree of "self-recovery".

- **Crew follow each other and the aircraft:** This technique makes monitoring of operations easer. It also allows for a simple recovery strategy that preserves some of the properties of the original schedule. However, due to the fact that rules applicable to various resources are very different, the most constrained resource will determine the structure of the plan. Also, the resulting plan can potentially be very tight for this one resource, which could make the entire plan unstable. Continental Airlines has implemented this technique in full. Most other airlines use some elements of it.

- **Out and back:** If an aircraft flies from a hub to a spoke and back to the same hub, these two flights can be canceled without affecting the rest of the aircraft schedule. If the same crew is planned for these two flights, the cancellation will not affect the rest of the crew schedule either. In the perfect hub-and-spoke network all flights are either in- or outbound from a hub. A pool of resources available at a hub allows for replanning in an event of disruption.

- **Stand by crew and aircraft:** A spare crew or an aircraft are valuable but very costly resources that can be used in case of disruption.

- **Extra buffers added to turnaround times:** Extra buffers are often added after frequently delayed flights, but they also provide slack in the schedule that can be used in recovery.

- **Increased cruise speed:** Aircraft have an interval of possible cruise speeds. Airlines will typically operate aircraft at the most economic speed, which will always be lower than top speed. Speed ups, which is the name for increasing speed, represent an additional cost due to increase fuel burn, but it may avoid higher costs in itinerary repair for aircraft, crew and passengers. Obviously this tool is more effective the longer the flight is.

## 2.3 Organisation of operations control

Most large airlines operate so-called Operation Control Centres (OCC) to perform on-the-day coordination of schedule execution. The purpose of OCC is to monitor the progress of operations, to flag up actual or potential problems and to take corrective actions in response to unexpected events. Representatives of the various key airline functions work together to ensure smooth schedule execution. The most common support roles in airline operations control are:

1. **Flight dispatch and following:** This is a prominent role in North America. The flight dispatcher shares responsibility for flight safety, follows preparation and progress of a number of flights and raises alerts with other areas when problems occur. In Europe, the aircraft control role usually performs the task of flight following, while flight planning and dispatch is often performed outside of the operations control area.

2. **Aircraft control:** Besides managing the aircraft resource, this is often the central coordination role in operations control. In Europe it is divided in long and short haul, in North America the most common division is according to geographical regions like North West, South West etc.

3. **Crew tracking:** The crew tracking role is responsible for the staffing of flights. Crew check-ins must be monitored and crew pairings must be changed in case of delays or cancellations. The stand-by crew resource must be dispatched and perhaps

reserve crew must be called in. In most airlines crew tracking is divided into cockpit and cabin crew.

4. **Aircraft engineering:** Aircraft scheduling is responsible for unplanned service and maintenance of the aircraft as well as the short term maintenance scheduling. Changes to the aircraft rotations may impact on short term maintenance e.g. because maintenance cannot be done at all stations.

5. **Customer service:** Decisions taken in the OCC will typically affect passengers. The responsibility of the customer service role in the OCC is to ensure that passenger inconvenience is taken into consideration in these decisions. Delays and cancellations will affect passengers who need to be informed and in some cases rebooked or provided with meals or accommodation. However, customer service is mainly provided at the gates and in customer service centers, which are not a part of the OCC.

6. **Air Traffic Control (ATC) coordination:** The ATC role is not a part of the OCC as it is common for all airlines and operated by a public authority, for example the Federal Aviation Administration (FAA) in the US and EuroControl in Europe. However, the ATC coordination becomes more and more important in North America, as airlines can actively participate in air traffic management through the Ground Delay Program by the FAA based on the Collaborative Decision Making (CDM) initiative [10]. In Europe, aircraft control typically takes this role.

Successful operation of an airline depends on coordinated actions of all supporting functions. However, each group typically operates under its own directive, with its own budget and performance measures. The most challenging job in the OCC is the one of a duty manager (in North America often called sector manager or SOC director) who is responsible for the overall coordination of operations, ensuring that all groups act as one team and strive towards common objectives. Exactly how the duty manager should perform the task, most of airlines leave up to the duty manager.

Currently, there are two alternative trends in operational management at the OCC. We will denote them *consolidation* and *cooperation*. In consolidation, the duty manager and representatives of a few key supporting functions essentially work at the same desk, thereby ensuring that all important decisions are taken by this team. In cooperation, a framework for cooperation between supporting functions can be established, promoting structured communication about the current operational situation, disruptions and available options. Both approaches provide a way of dealing with complexity, i.e. communication between decision makers, high degree of uncertainty and high volume of information. In the consolidation approach, the first two issues are addressed directly in one team.

For the different stakeholders in the day-of-operations process up-to-date information is crucial. Especially for crew controllers and the aircraft (AC) controllers online information is vital in the effort to master last minute changes. A wealth of relevant data is stored in the data warehouses of large airlines, and by displaying the right information as quickly as possible substantial support can be given to the controllers.

Most often AC controllers have access to Gantt charts that display important information like status of the flight and changes as they happen. The system updates as new information about the flights become available, thereby helping the controller to track the current status of his/her fleets. For trans-Atlantic flights, satellite navigation can help the AC controller in keeping track of the current position of the flights. This is generally not part of the AC system, but rather a separate program on the desktop of the controller. For busy airports like London Heathrow, a useful tool for the AC controllers is to listen in on the communication between ATC and the aircraft. This can identify the position of an aircraft in the holding pattern, thereby making it possible for the AC controller to come up with qualified estimates of a possible arrival time.

Other groups like crew and passenger controllers are often left with a lesser alternative. They can receive updated information but only by querying the information systems themselves hence the controller will send querying-commands to the relevant system in order to obtain the information needed.

In some cases, information that, by definition should be identical is not always measured in the same way. Thereby data such as departure time for crew and aircraft can seem inconsistent although the crew was on that aircraft. In day-of-operations this poses a challenge to the work of the controllers as they might have to act on last minute information.

While information from engineering is typically also available for the OCC, information from less critical functions like catering, cargo and gate staff is not generally available. Here, communication between relevant departments has to be established manually.

# 3 Problem Definition and Objectives

In this section we describe disruption management and its objectives. Where the aim of section 2 was to describe current airline practice, the aim of this section is to present a more abstract problem formulation. In section 3.1 a conceptual model for the disruption management process is presented and the steps of the process are described. In section 3.2 we present the objectives of disruption management and section 3.3 discusses the extent to which disruption management can be automated. Finally, in section 3.4, we discuss to what extent disruption management can be facilitated by proactive decision making.

## 3.1 The Disruption Management Process

We view disruption management as an ongoing process rather than a single problem, which can be formulated explicitly. The disruption management process is illustrated in Figure 2.

An airline must constantly monitor its operations. The state of operations is defined by the planned events (time table, fleet and tail assignment, crew scheduling etc.) and the actual events. The actual events are often recorded in an on-line message stream and the average message density is often more than one message per second. Some actual events will indicate a discrepancy between plans and operation and raise question whether it is necessary to do something. This question could also be raised by the lack of an expected event, say a crew member who did not report for duty, or by the need for taking a decision, such as to call in additional stand-by crew, before a given point in time. We will denote these time triggers, because the possible need to do something, in this case, is driven by the time rather than by an unexpected event.

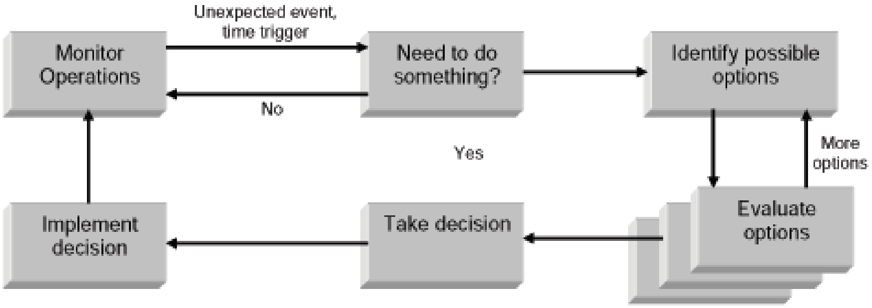


Figure 2: High-level view of the disruption management process.

It is not necessary or possible to act on all unexpected events or even time triggers. Some unexpected events, such as minor delays, do not require changes of plans and cause very limited inconvenience for passengers. Other events may be quite serious but it may not be possible to do anything about them. In case it is necessary to do something about the event or time trigger, we will denote it a *disruption*. The first thing to do is to identify the possible relevant actions and to evaluate these. The evaluation will involve evaluations from the passenger, crew and aircraft perspective and possibly even from other perspectives. These evaluations may result in proposed changes to the option. From the passenger perspective it may, for example, make sense to delay an outbound flight (ie. a flight out of an airlines hub) to ensure that passengers on a delayed inbound flight will be able to make their connection. This option must then be evaluated from the crew and aircraft perspective. In principle, this process can continue, until an option, which is legal and acceptable from all perspectives, has been found.

Based on the agreed option, we can decide whether it is necessary to do something now or whether we can postpone the final decision, i.e. plan, but not commit to the plan yet. This is clearly dependent on the actions considered. If we intend to change the schedule of a crew member, a two hour notice may be required whereas a crew member on stand-by could be assigned with a one hour notice. In any case, we will try to avoid to committing the resources earlier than necessary. Once a decision has been taken it must be implemented and the monitoring must continue.

At this level of abstraction, the disruption management process is not so different from most control processes in complex systems involving humans. The most important distinct features are the very broad array of potential options and the computational complexity of assessing the impact of each of these options.

## 3.2 The Objectives of Disruption Management

One of the difficult aspects of disruption management is to specify the objectives. Objectives fall in three broad categories:

- "Deliver the customer promise", i.e. get passengers (and their luggage!) to their destination on-time with the booked service level.

- Minimize the real costs including excess crew costs, costs of compensation, hotel and accommodation to disrupted passengers and crew, and tickets on other airlines.

- Get back to the plan as soon as possible.

The first two objectives are quite natural and easy to agree on. They can also be quantified and, at least in principle, be measured in the same unit. Even though there is a lot of judgment involved in quantifying the soft cost of a passenger delay, it is clear for everybody that there is a distinct trade-off between "delivering the customer promise" and keeping cost down. The third objective is harder to quantify and the motivation for this objective is also more debatable.

Getting back to plan is conventional airline wisdom. In some cases it is necessary because it may not be possible to change crew schedules without long notice. It may for example, be essential to ensure that a crew member can fly the rest of the pairings on her monthly roster even if the current pairing is disrupted. Getting back to plan may also make disruption management easier in the sense that it is easier to decide what actions to take. The complexity of the problem is reduced. In some sense this is also the drawback of getting back to plan. The original plan was (hopefully!) optimal in the situation before the disruption occurred, but in case of a major disruption it may be relevant to completely discard the old plan – at least for the resources where this does not cause major inconvenience to humans. Aircraft tail assignment and routing as well as gate allocation are obvious examples.

### 3.3 To What Extent Can Disruption Management be Automated?

Due to the complexity of disruption management, there is little reason to believe that it can be automated to the same extent as e.g. crew and fleet scheduling in the foreseeable future. Realistic approaches to disruption management must involve humans in the key parts of the process, in particular:

- In many cases humans must determine whether a particular event or sequence of events should be characterized as a disruption one must act upon. Typically this will be triggered by a message from computerized systems consolidating operational data, but the role of the human is to determine whether events are sufficiently serious to require an action and also to define the scope of the disruption. Several apparently unrelated events may for example be relevant to be treated together as one disruption because the same resources are likely to be involved in the resolution of the disruption.

- Humans must be involved in the actual decision making and determination of when decisions must be taken. This is partly because humans will be responsible for the consequences of the decision but also because the decision in many cases will be partly dependent on information and judgments which will not exist in computer systems.

- In the foreseeable future the implementation of a decision will require human communication.

We conclude that the main roles for computer systems in disruption management are:

- To process the large amounts of operational data and present potentially critical events for a human.
- To generate and evaluate possible actions for a well defined disruption.

### 3.4 Proactive Decision Making and Disruption Management

In disruption management we try to deal with the disruptions when they have occurred. The aim of proactive decision making is partly to avoid disruptions in the first place, partly to limit the impact of disruptions when they occur. There are several ways of practicing proactive decision making. Some of the most important include:

- **Robust planning**: Slack should be built into the plan where it is known to be particularly vulnerable to disruptions.
- **Avoiding operational complexity**: An airline which operates a point-to-point network with one class of service with one fleet and flight and cabin crew that follow the aircraft as much as possible can limit the impact of disruptions much more than an airline with a complex route network, many different fleets, several classes of service and highly optimised crew and fleet scheduling.
- **Exploit probability of events**: Probability of events can be utilized as well in planning as in disruption management. The cost of a pairing could for example be viewed as the expected cost of executing the pairing rather than the cost of executing it as planned.
- **Planning for alternative scenarios**: One could, for example, plan which flights one would cancel if it for some reason would be necessary to reduce capacity by, say, 50% the next day. Here, the advantage is that there is more time to do computations now rather than tomorrow when the decision may have to be taken within the next few minutes.

As discussed in section 2.2, robust planning and avoiding operational complexity are well known techniques in practice. Planning with probabilities and planning for alternative scenarios are not yet in widespread use.

## 4 Review of the Academic literature

In this section we review previous academic research on methods for disruption management. Research on aircraft recovery, crew recovery and passenger recovery is reviewed in 4.1, 4.2 and 4.3 respectively. In 4.4, research on disruption management of multiple resources is reviewed. Generally, in the disruption management literature passengers are given a low priority. Furthermore, research on the recovery operation to this date only deals with a single airline. Cooperation between airlines is not supported.

For a more in-depth and theoretical description of the academic research within disruption management we refer to the review by Clausen et al. [14].

Beside the literature reviewed in this section the conferences of the The Airline Group of the International Federation of Operational Research Societies (AGIFORS) often feature relevant presentations either at the annual symposium or the meetings of the airline operations study group. For further information see www.agifors.org.

Presently work on integrated approach is still a challenge as no real-life results are reported yet. [23] presents a framework but parts of the framework still needs to be implemented and tested. The aircraft recovery problem has be received significant attention probably because it is the easiest resource due to the lowest complexity in rules and the smallest numbers and also because in todays OCC aircraft is the "main" resource which is fixed first and foremost. Crew recovery to a large extent based on the same ideas used in the planning phase have emerged, but the problem has not attracted nearly the same attention, which also holds for the passenger recovery problem. This could reflect "old time" thinking where passengers only interesting when crew and aircraft is available. It seems that the challenges of integration, crew and passenger is ready for more research.

## 4.1 Aircraft Recovery

By far the most work on operational recovery problems has been reported on the aircraft resource. Since crews can be repositioned fairly easy and standby crews are often available, the aircraft are seen as the scarce resource.

Teodorovic and Guberinic were among the first to study the aircraft recovery problem. In their paper [39] often one or more aircraft are unavailable and the objective is to minimize the total passenger delays by reassigning flights and retiming flights. The model is fundamentally a network-model with additional constraints. It is solved by a branch-and-bound method. However, only a single extremely simple example of 8 flights is considered.

An extension of [39] is [40] where Teodorovic and Stojkovic consider aircraft shortage. Using an algorithm based on a lexicographic ordering of the flights, the problem is solved by a heuristic based on dynamic programming. This model incorporates airport curfews. The constructed model allows for cancellations, retimings and swaps. The main objective is to minimize the number of cancellations. If there are several solutions with an identical number of canceled flights, a secondary objective of minimization is the total passenger delay. The authors devise a greedy heuristic that sequentially builds the chain of flights to be serviced by each aircraft. After a chain for each aircraft is found, the flights left unassigned are canceled. No experiments are reported.

Jarrah et al. [19] develop two network flow models – a delay model and a cancellation model – to handle the effects of aircraft shortage. Both models allow for the use of standby aircraft, but neither considers crew nor maintenance issues. The objective of both models is to minimize the costs associated with the recovery, i.e. the swap and ferry costs in both models and in addition here to delay costs in the first model and the cancellation costs in the second. Both models are minimum-cost flow network problems and can thus be solved efficiently to optimality. The drawback is that one model handles retiming only while the other handles cancellations only. Cost reductions between 20% and 90% are indicated by the computational results for the delay model when comparing with an unoptimized schedule. The work of Jarrah et al. is implemented in the System Operations Advisor deployed at United Airlines. Rakshit et al. [31] describe the interface and how the software is used. Another paper focusing on the interface of a decision support system for airline operations control is the one by Mathaisel [29].

In two papers [15, 16] the delay model of Jarrah et al. [19] is extended in order to incorporate cancellations and multiple airports. The model is a quadratic binary programming model. Here flight revenue with subtracted swap and delay costs is maximized. As for Jarrah et al. [19] the presented model cannot cater for crew and maintenance, and Løve and Sørensen in [27] showed that the described method have serious deficiencies. From [15, 16] it is not clear what kind of scenarios that are studied, since the computational experiments start with a randomly generated non-optimal schedule. This schedule is then improved heuristically.

In [28] Løve et al. present a heuristic for the aircraft recovery problem based on local search. The schedule is represented by the lines of work for each available aircraft. In order to resolve infeasibilities, cancellations, delaying or reassignment of aircraft are considered. Reassignments both within a single fleet or between fleets can be handled. The objective is to minimize recovery costs as costs are put on delays, cancellations and swaps. It is even possible to put costs on the individual flights in the recovery period in order to weight the importance of the different flights. The model does not consider maintenance. It was tested on the short-haul operation of British Airways (79 aircraft, 44 airports, 339 flights) and achieved promising solutions within 10 seconds.

In [3, 4] of Tobias Andersson et al. the aircraft recovery problem is modeled as a multi-commodity flow formulation with side constraints. The model can be seen as a mixed integer multi-commodity flow formulation with the side constraints that each aircraft is a commodity. Side constraints are also used to model possible delays. The model is capable of retiming and cancellation of flights as well as reassigning flights to aircraft. The thesis contains three solution methods for solving the model: a Lagrangian heuristic, a method based on Dantzig-Wolfe and finally a heuristic based on Tabu Search. For the Dantzig-Wolfe method four different solution strategies to the master problem are proposed. Computational results are based on data from a Swedish domestic airline (data instance characteristics: 13-30 aircraft, 2-5 fleet types, 98-215 flights, 19-32 airports). The Lagrangian heuristic performs so poorly that detailed results are not published. While the Dantzig-Wolfe-based methods are good for small problem sizes, larger problems have to be solved by Tabu Search. For the smallest problems the solution times are below 10 seconds for all methods, but as problem size grows the Danzig-Wolfe-based methods gets slower and use as much as 1100 seconds, while the Tabu Search remains around 10 seconds.

Argüello et al. [6, 7] present a method based on the metaheuristic GRASP (Greedy Randomized Adaptive Search Procedure) to reschedule the aircraft routings during an aircraft shortage. The heuristic is capable of canceling and retiming as well as swapping flights (also between different fleet types). Maintenance and crew considerations are not implemented. The goal is to produce a recovery schedule in order to restore the original schedule by the following day. The cost to be minimized includes measures of passenger inconvenience and lost flight revenue. Computational experiments are reported for a fleet of 16 aircraft, 42 flights and 13 airports. Using only 10 seconds running time for each problem instance the heuristic finds, according to the author, very good solutions typically within 10% of optimality.

Based on the same model Bard et al. [8] solves the integral minimum cost flow model with additional constraints using LP-relaxation and Branch-and-Bound. The method is tested on data from Continental Airlines. It is tested on one fleet (B737-100) with 162 flights covering 30 airports by 27 aircraft. 427 test cases are generated. The results are generally encouraging with respect to quality, execution times are up to 750 seconds on a Sun Sparc 10.

In the papers of Yan and Yang [46] and Yan and Tu [45] four models are developed for the case of the temporary unavailability of one single aircraft. The models are developed specifically for small airlines. All models are dealing with schedule perturbation problems. In the first model, it is possible to cancel flights in order to repair the schedule. The second model has an increased complexity and allows for both the cancellation of flights and ferrying of spare aircraft. The third model considers cancellation and retiming, and the last model incorporates all of the possible decisions and adds ferrying of aircraft. In all models it is possible to swap within a fleet. The objective in all four models is to minimize the cost of schedule repair, which includes passenger revenue. The first two models are rather simple and are built as network flow models which make it possible to solve them to optimality very fast, while the two other models contain side constraints making them hard to solve. They are solved heuristically using Lagrangian relaxation and subgradient optimization. In all models neither crew nor maintenance is considered. In Yan and Tu [45] a multi-fleet version of the model described above is presented, where a larger aircraft type can be assigned to a flight that originally was planned to be serviced with a smaller aircraft type. Furthermore multi-stop flights can be reduced by deleting some or all of its stops.

The case study presented in [46] is based on China Airlines data. The fleet consists of 12 aircraft serving 15 cities and covering 319 flights a week. Models 1 and 2 solve the instances to optimality while 3 and 4 get within 1% of optimality in a matter if minutes. For [45] the experiments are performed on a test set of 26 aircraft divided into 3 different fleets performing 273 flights a week. In total the developed methods were tested with 534 different scenarios. All problems were solved to optimality or at most 1% from optimality within 5.5 minutes.

In [47] Yan and Young consider multiple aircraft types, but aircraft swaps between fleets are not allowed. This paper also contains the first model that provides a delay and cancellation plan simultaneously. In the objective profit is maximized and the cost of cancellation and/or delay is subtracted from the airline revenue. The model is basically a minimum cost flow problem with side constraints, and it is solved by Lagrangian relaxation based on a subgradient approach. The model does not take maintenance, crew restrictions nor passenger connections into account. In Yan and Lin [44] the same models as discussed above are used to solve the special situation when an airport is temporarily closed. The closure of an airport is an example of a large-scale disruption, which often has to be solved by changing the destination airports for the affected flights. The model presented only allows the usual flight swaps, retimings and cancellations, so flights arriving or departing from the closed airport have to be canceled or delayed.

Thengvall et al. [38] uses the models presented in [46, 45] and extend them to incorporate the ability to penalize deviations from the original schedule. As all other models presented so far crew and maintenance are not considered in a model that can handle cancellations, retimings and flight swaps. The objective is to maximize the passenger revenues subtracting the costs of retimings. Integer solutions to the model are obtained by a heuristic, in case the LP-relaxation results in fractional solutions.

Rosenberger et al. [32] propose a model which addresses each aircraft type as a single problem. The model uses an approach traditionally seen within planning problems (see eg. [21]), namely a master problem being a set partitioning problem (each flight is either flown by an aircraft or it is canceled) and a route generating procedure. The model seeks to minimize the cost of cancellations and delays. In order to be able to solve the master problem within the time requirements, a heuristic is used to select only a subset of aircraft to be involved in the set partitioning problem. This approach results in running times between 6 and 16 seconds for 3 real-size problem instances. The proposed model is tested using the simulation environment "SimAir" (see Rosenberger et al. [33]). A total of 500 days of operations for three fleets are simulated. The test datasets range from 32 to 96 aircraft servicing from 139 to 407 flights.

Talluri [37] deals with the problem of changing the aircraft type for a single flight. Although the aircraft plan is fixed for the day-of-operations events such as an increased demand at a single flight may imply that it is desirable to change the aircraft type. The developed methods have to respect a time limit of 2 minutes. Talluri develops two algorithms: The first algorithm determines (in polynomial time) whether an aircraft-type swap and a swap-back can be accomplished before the overnight stop. This is often desirable due to engineering issues. If the algorithm cannot find a solution another algorithm allowing at most $k$ overnight changes is invoked for ever increasing $k$. Maintenance and crew considerations are not implemented. Testing is very limited and documented with only one instance. For a connection network consisting of two fleet types, 700 arcs and 200 nodes 10 solutions are found within 10 seconds on an IBM RS560.

Luo and Yu [25] and [26] both address the problem of schedule perturbation resulting from the Ground Delay Program of the Federal Aviation Authorities. At an airport each operating airline has each day a number of assigned slots for landing and take-off. The slots exactly match the activities of the airline. The arrival slots for the airlines may, however, be changed. Then slots may be moved in time and possibly canceled. The problem for each airline is now to determine the assignments of flights to available slots in order to minimize inconvenience and knock-on effects. Hence, delays are not directly connected to a specific flight leg but to the fact that the landing slots for each airline are moved in time. The problem is therefore to reschedule the flights. In [25], the subproblem in which aircraft and all crew are scheduled together is considered. A number of different objectives are discussed. The problem is an assignment problem and very efficient solution methods are readily available. The paper is theoretical and methodological in nature, and no implementations or experiments are reported. Considering schedules, in which aircraft and crew are scheduled separately, the problem becomes more complex. If the objective is to minimize the maximum delay of out-flights, which is crucial because these delays are the ones inflicting down-line knock-on effects, the general problem is strongly NP-hard. In [26], a special variant of the problem is shown to be easy, and a heuristic is developed for the general version. The paper presents the result for a real-life problem from American Airlines with 71 incoming flights. A large improvement in the number of aircraft delayed more than 15 minutes compared to the original schedule is achieved by the proposed methods. The solution time is approx. 15 seconds.

## 4.2 Crew Recovery

Far less work is published on the crew recovery problem. The problem is far more complex due to the numbers of cabin crew and the more complex rules and regulations for crew. Wei et al. [42, 48] develop an integer programming model and an algorithm for managing crew in case of a disruption. The model can be viewed as an integer multi-commodity network flow problem, where each crew member represents a commodity. A second set of constraints is flow conservation restricting each crew member to one pairing. The developed heuristic is based on a branch-and-bound framework. The model repairs broken pairings and assigns crew to flights that are not covered (and minimizes the number of uncovered flights in case not all can be covered). The algorithm manages crew on each flight as one unit and can not take individual rostering issues into consideration. Furthermore it is assumed that crew are only licensed to one aircraft type. The system is able to present the controller with multiple (up to 3) different solutions. On scenarios from Continental Airlines scenarios of 1 to 40 affected flights are tested. Execution times reported are between 0.1 seconds and 442 seconds. For scenarios up to 20 affected flights the heuristic constructs an optimal solutions.

In two quite similar papers Stojkovic et al. [36, 35] solve the crew recovery problem so that all flights are covered at a minimum cost while minimizing the disturbances of crew members. This is done by solving the crew pairing and crew assignment problems simultaneously denoted the "personal pairing" problem. Disrupted pairings and some additional pairings are dissolved and personal pairing problems are solved using the flight legs of the dissolved pairings. As this is done within a tight time frame the problem size is smaller than the original pairing and assignment problems. The basic underlying model is a generalised set partitioning model and the papers report solution times of a few seconds on real world airline problems for pilots ([35]). The model allows for the cancellation of flights whereas retiming is not possible. For cabin crew the solution times reported in [34] are above 5000 seconds for the developed heuristic – again achieved on real world airline problems.

Airline crew recovery is also the focus of [24]. Here Lettovsky et al. present a method based on an integer programming formulation. In a preprocessing step a subset of crew schedules are extracted for rescheduling. A fast crew-pairing generator is build enumerating feasible extensions of partially flown crew schedules. The integer programming model is relaxed and several branching strategies are tested. The objective is to disturb the current schedule as little as possible. As with [36, 35] delays are not considered by the model. The developed methods are tested on data from a major US-based airline based on a schedule consisting of 1296 flight legs and 177 pairings. Small problems are solved within 6 seconds, while larger problems require as much as 115 seconds.

Medard and Sawhney [30] considers the crew recovery problem and stress that the problem is structurally different from the crew pairing and rostering problems because contrary to the planning phase these two subproblems have to be solved at the same time in the recovery phase. This means that both rules on the pairing and the rostering level have to be respected. Thus, they note that the recovery challenge is to merge the pairing characteristics into a rostering problem which is modeled at the flight level. Medard and Sawhney propose an optimization model which is the flight-based equivalent to the original pairing-based rostering model, where the flights replace the pairings. The optimization model is a set covering model which is solved using column generation. The authors consider two different schemes for generating the columns. The methods are tested on small to medium sized scenarios ranging from 14 to 885 planned crew members with up to 77 illegal rosters. The results are encouraging however for some of the more complicated scenarios the time limit of a few minutes is not respected and the authors conclude that the column generation schemes must be refined for instance by using crew specific information.

### 4.3 Passenger Recovery

The only reported results on the passenger recovery problem is [23]. Here a Passenger Flow Model (PFM) evaluates passenger impact. The anticipated passenger demand will be based on an origin-destination booking matrix. The main objective of the PFM model is to maximize the recovered passenger revenue by reassigning disrupted passengers to available seats. The PFM does not consider passenger re-accommodation explicitly, but merely assesses the financial impact of schedule changes. PFM is a three-stage procedure. First passenger aggregations based on itineraries are performed. Then feasible paths through the (changed) network of the airline are determined. Finally, an optimisation model is used to determine the most beneficial seat allocation based on the generated itineraries and their corresponding loads. The model is based on available data on passenger itineraries, flight bookings, and flight operations information. There are no computational tests reported on the PFM.

### 4.4 Recovery of Multiple Resources

In a paper by Teodorovic and Stojkovic [41] the generation of a solution for several resources is considered. This is the first effort to consider the integration of several resources published in the literature. This solution also considers crew and maintenance. The problem is solved sequentially using a heuristic by first making a new crew schedule after which a new aircraft schedule is created and checked for maintenance feasibility.

Alternatively it is possible to schedule the aircraft first and then assign crew to aircraft. Teodorovic and Stojkovic claim that this alternative behaved much less efficiently in experiments. To check crew legality while forming aircraft schedules is time consuming, while ignoring crew legality will usually result in infeasible aircraft schedules. No model is actually presented by the authors and they restrict themselves to illustrate the effectiveness of the model and the solution strategy by giving numerical examples. The objectives are the same as for [40].

In the thesis [23] by Lettovsky a mathematical model is developed in an effort to solve the integrated problem of crew and aircraft. The mixed-integer programming model is very large and computational intractable for anything but unrealisticly small problems. Therefore Lettovsky suggests solving the problem using a decomposition scheme. The decomposition scheme is controlled by a master problem called the Schedule Recovery Model. It provides a cancellation and retiming plan satisfying imposed airport curfews and assigns equipment types. Thereafter the subproblems for crew, aircraft, passenger etc. can be solved separately given a solution to the master problem. The solution algorithm applies Benders' decomposition to a mixed-integer programming formulation of the master problem. Three subproblems are formulated in the thesis:

- **ARM**: The Aircraft Recovery Model. Here new flight links are generated that satisfy maintenance requirements.
- **CRM**: The Crew Recovery Model. New crew schedules complying with union and governmental regulations are created. This is the model presented in [24].
- **PFM**: The Passenger Flow Model. New passenger itineraries are generated which comply to seat availability for each flight.

In the thesis only the CRM is implemented and tested. The method appears effective. Conclusions are based on nine computational experiments from [24].

To modify the fleet assignment due to the fluctuating passenger demand pattern, Klincewicz and Rosenwein [22] discuss the possibility of modifying the daily airline schedule and assignment. This can be viewed as a fleet/passenger recovery model. In their model it is possible to add or cancel a flight, upgrade or downgrade the passenger capacity on a flight (i.e. change the aircraft type). As input the model needs the schedule, the fleet assignment and what type of exception (adding, canceling, upgrading or downgrading) that is wanted on which flight. Based on a network flow model, a new fleet assignment is generated, albeit without considering crew and maintenance.

A recent contribution by Bratu and Barnhart ([9]) describes two models for integrated recovery. The models are focused on passenger recovery but also incorporated to a certain extent rules and regulations on aircraft and crew, eg. reserve crews are incorporated but not the ability to recover disrupted crew. Two models are developed. In the Passenger Delay Metric (PDM) model delay costs are more accurately computed by explicitly modelling passenger disruptions, recovery options and delay costs then in the Disrupted Passenger Metric model and (DPM). Both models have an objective function incorporating operation costs and passenger recovery costs. The models are solved using OPL Studio. Multi-day test cases are presented using an Operations Control Center simulator developed by Bratu. Airline data represents a domestic U.S. operation involving 302 aircraft (divided into 4 fleet types), 83869 passengers on 9925 different itineraries a day, 74 airports and 3 hubs. Different scenarios based on the level of disruptions are presented. Execution times are in the range of 200 to 5000 seconds each time one of the models needs to be solved. Conclusions are the PDM cannot be used in an real-time environment, whereas DPM is fast enough to be used in a recovery situation.

In [11] and [12] Clarke present a model and algorithms for the airline schedule recovery problem, i.e. the problem of aircraft reassignment for all operational aircraft in a fleet in the aftermath of irregularities. The model is an integer program and different solution strategies are discussed and tested. Flights can be canceled or delayed and a number of constraints are introduced to ensure feasibility with respect to aircraft maintenance, accommodation of passengers, crew availability, slot allocation and gate allocation. Hence, the model capture a very large number of resources, but has a rather simplistic model of all resources but aircraft. The model and algorithms have been tested and validated on operational data from a major US domestic carrier.

# 5 The Descartes Project

The Descartes (DEcision Support for integrated Crew and AiRcrafT recovery) research project ran over 3 years from 2000 to 2003 between British Airways (BA), Carmen Systems, and the Technical University of Denmark. The project was financially supported by the European Union under the programme "new methods of organisation, work and capital improvement". A detailed description of the project and its results can be found in the final project report to the European Union [17].

The main objective of the Descartes project was to develop a disruption management system based on a holistic approach. The system should integrate the decisions of the different resources in one integrated feasible decision. The main focus was on the four key resources of the problem namely aircraft, flight and cabin crew, and passengers.

## 5.1 The Descartes Architecture

The Descartes system is build as a "suite" of systems. It consists of:

- **Dedicated solvers**: These systems are only able to handle single resources like aircraft or flight crew. During the project solvers for aircraft, crew and passengers denoted Dedicated Aircraft Recovery system, Dedicated Crew Recovery system and Dedicated Passenger Recovery system were developed.
- **Integrated Recovery**: Based on solutions from the dedicated solvers, integrated recovery constructs an integrated solution. This is done via a messaging system specifying single resource problems, that needs to be solved by one or more of the dedicated solves.
- **Integration layer**: All systems are integrated with the managers' view of the operation by the communication architecture known as the "umbrella". Communication to and from the dedicated solvers is processed via the disruption management systems.
- **Simulation**: Simulation makes it possible on a step-by-step basis to monitor the operation and thereby verify the robustness and attractiveness of the plans.

An overview is presented in Figure 3. Table 1 describes the abbreviations used.

| | |
|---|---|
| FC | Flight crew |
| CC | Cabin crew |
| AC | Aircraft |
| DMS | Disruption Management System |
| DCR | Dedicated Crew Recovery |
| DAR | Dedicated Aircraft Recovery |
| DPR | Dedicated Passenger Recovery |

Table 1: Abbreviations used in Figure 3.

One of the advantages of this approach is the possibility of including existing dedicated solvers into the Descartes system. If the airline already has developed or purchased

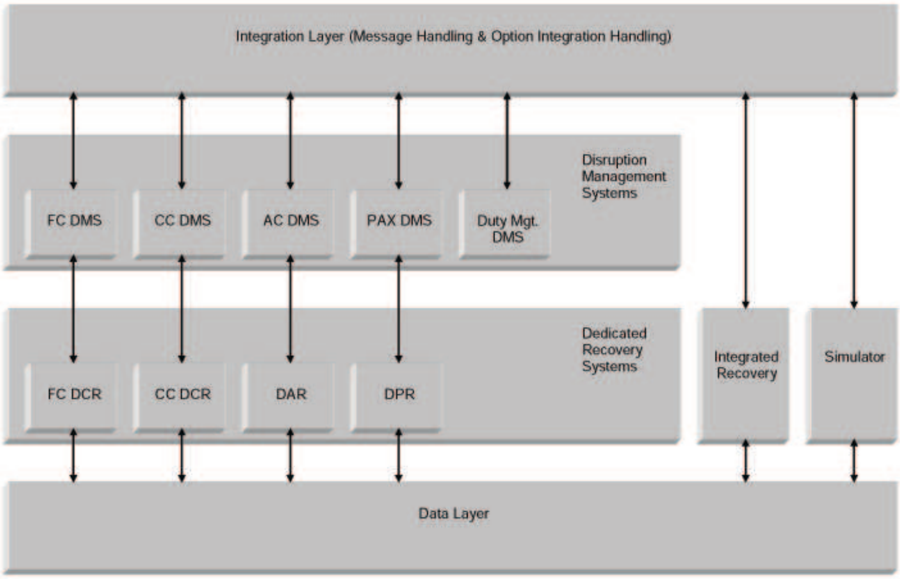


Figure 3: Overview of the architecture of the Descartes system.

dedicated solvers they can replace the solvers developed in the Descartes project and be incorporated into the Descartes system through an API.

The prototypes for the Descartes Passenger Recovery System, the Descartes Aircraft Recovery System the Descartes Crew Recovery System and the Integrated System have all been tested using "business experiments". The experiments were conducted by developing realistic scenarios (showing differing levels of disruption) in cooperation with Operations Control business experts at British Airways. These scenarios were based on the Operations Controllers experience and knowledge. The scenarios were then solved both manually (by an Operations Controller) and automatically (using a solver) and the results compared.

The sections 5.2 to 5.4 describe the different solvers. Each section includes an overview of the business experiments together with findings and conclusion on the experiments. Section 5.5 discusses the possibilities for the development of systems for integrated recovery.

## 5.2 Dedicated Passenger Recovery System

The purpose of the Dedicated Passenger Recovery solver (DPR) is to evaluate possible recovery options (which may be generated manually or automatically by one of the other dedicated solvers in the Descartes architecture) from the perspective of the passengers and to propose an optimal rebooking plan. For each recovery option to be evaluated, the DPR calculates the passenger inconvenience cost plus any real costs associated with this recovery option by finding an optimal rebooking plan for the recovery option. The optimal rebooking scenarios are created based on the following metrics:

- The cost of passenger delays. The cost depends on the delay at the final destination of the passenger. This is not the traditional way to measure delay in airlines, but we find this is a more relevant measure than the delay of the aircraft compared to schedule. The delay cost calculation also takes into consideration the commercial value of the passenger – for example based on the booked fare class and frequent flyer information. It is clearly a highly subjective issue how to derive a formula for the cost of passenger delays, but it is well established that there is a long term cost associated with delaying passengers.

- The cost of passenger off loads. There may be several real costs as well as loss of goodwill associated with offloading a booked passenger.
- The cost of meals and hotel accommodation for severely disrupted passengers. In many cases the airline is required to or volunteer to provide passengers with meals and accommodation in case of disruptions. According to a recent initiative of the European Parliament such services will become mandatory.
- The cost of passenger upgrades and downgrades. These costs are partly real costs for upgraded catering and downgrade compensation, but there is also loss of goodwill costs associated with downgrades.

These costs together determine how much, in monetary terms, the disruption from a passenger perspective is costing. In the experiments carried out with BA data the dominating factor was passenger delays, but for a no-frills airline the unavoidable real costs would probably dominate.

### 5.2.1 The underlying optimization model and solution methods of the DPR

In its most general form the passenger recovery problem can be formulated as a multi-commodity flow problem, where each passenger is represented by a resource. For a discussion of the multi-commodity model and solution approached we refer to Ahuja et al. [2]. A flight is represented by a start and end node connected by a capacity constrained arc, whereas possible connections between flights are represented as uncapacitated arcs. Each passenger's start and end are represented with nodes. Special offload arcs are introduced to ensure feasibility of the model.

The four cost components discussed above can with small approximation be associated with arcs in the outlined network. The cost of passenger delays can all be associated with arcs terminating in the end destination of a commodity, as delays are only measured at the passengers' destination. Passenger offload costs are associated with the offload arcs. Meal and accommodation costs will always be associated with connections between flights or a delayed initial flight and can therefore be associated with arcs. Upgrades and downgrades represent a slightly more difficult problem, depending on the configuration of the aircraft. There are three different cases to consider:

- The number of seats in the different classes is fixed. This is typically the case for long-haul aircraft, where the first class cabin, the business class cabin and the tourist class cabin are physically separate units, which cannot be enlarged or reduced. In this case each cabin can be treated as a separate flight arc in the network and upgrade and downgrade costs can be modeled correctly.

- Seats can be converted from one class to another at a one to one ratio, i.e. a tourist class seat can be converted to a business class seat and vice versa. This is sometimes the case in short-haul operations. In this case the flight is modeled with one arc where the resulting number of tourist and business class seats is a simple consequence of which passengers the flight carries in the optimal solution. In practice it is only possible to convert rows of seats (by “moving the curtain”), but this cannot be captured within the multi-commodity flow model. This approximation amount to a possibly additional upgrade of a part of one row worth of tourist class passengers to business class – i.e. a quite insignificant approximation.
- Seats can be converted from one class to another but not at a one to one ratio. Frequently a row of five or six seats in tourist class will convert into four seats in business class. This cannot be captured within the multi-commodity flow model and either the model must be extended or the “curtain positioning problem” must be solved as a separate optimization problem.

The multi-commodity flow problem is a hard optimization problem, so within the Descartes project different simplifications of the model were studied. Similar passengers can be aggregated, thus reducing the number of commodities and different parts of the network can be optimized separately, thus reducing the size of the optimization problem. Depending on the degree of approximation, the problem may be reduced to different variants of the easily solvable single commodity flow problem. Fortunately the BA route network is quite simple with virtually all flights originating or terminating in London so a number of simplifications, which may not be universally applicable, were possible.

### 5.2.2 Experimental Results with the DPR

The DPR developed in the Descartes project have been benchmarked against the current practice at BA. The business team at BA produced a number of scenarios that reflected the types of everyday disruption problems faced by the team. These scenarios ranged from the very simple type of disruption to more complex problems where several flights had to be canceled. These were then run by entering the scenario into the DPR and at the same time giving that scenario to the customer service recovery manager (CSRM), ensuring that both the DPR and the CSRM received the same information. This was as close to simulating the live operational environment as possible, without actually running the system within the operation. The outcomes were then compared and analyzed. The solutions proposed by the CSRM and the DPR, respectively, were compared with respect to the agreed cost function as well as with respect to the solution time.

In all cases the CSRM used approximately 45 minutes to solve the problem whereas the DPR used less than one second for the simplest case and almost ten seconds on the most complex one. In the simplest case the proposed solutions were identical, but in the more complex cases the DPR solutions were either somewhat better or much better. The differences in the proposed solutions were analyzed and it was established that DPR solutions were superior due to a more exact assessment of the total commercial value of the passengers and due to a better analysis of the rebooking possibilities, especially regarding connecting passengers.

### 5.2.3 Conclusions

The Descartes consortium found the DPR experimental results extremely encouraging. This is due to the vast time savings using the DRP compared to manual analysis and also to the documented improved solution quality. As a conclusion of these results, the DPR as a stand-alone tool is believed to bring business benefit and add value to decision making. By using this tool, it would allow the Customer Service Recovery team a real voice in the decision making process during operational disruption, which currently they do not have in reality. As the solutions are generated so quickly, the system would enable the CSRM's to evaluate many options, in order to come up with the best solution from a passenger perspective, in all types of disruption from minor or major.

## 5.3 Dedicated Aircraft Recovery Solver

The objective of the Dedicated Aircraft Recovery Solver (DAR) prototyping work was to develop an automatic decision-support tool capable of proposing alternative action plans to recover an infeasible aircraft schedule back to feasibility. DAR is capable of employing any combination of the key schedule recovery techniques used in practice, namely flight delays, cancellations, aircraft type changes and aircraft registration (tail number) changes within a fleet. Each of these actions incur a user-specified penalty in DAR and the objective for DAR is to consider these factors together with other relevant criteria such as passenger loads and values, plan quality criteria, resource constraints, etc. and return multiple, feasible, low-cost solution options. The scope of DAR developed within the Descartes project was defined as the BA London Heathrow short-haul operation.

### 5.3.1 The DAR model and solution approach

The DAR solver developed in the Descartes project is based on an extension of the local search heuristic presented by Løve et al. [28]. A heuristic approach were chosen due to the time requirements. The solver should be able to generate recovery options within 2-3 minutes.

The model used is an extension on the time-line network proposed in Cao and Kanafani [15] and [16]. The network consists of nodes that represent the aircraft, the flights and the surplus aircraft (standby aircraft). Furthermore, the network consists of sink nodes that indicates the end of a link of flights. Also, the network holds a number of cancellation nodes which is used in case of having to cancel flights. The arcs that connect the aircraft and the flight nodes represent that the particular aircraft is assigned to the flight to which it is connected. The heuristic generates a feasible flight schedule by changing these assignments through simple swaps. The model allows retimings, cancellations and fleet swaps. Swaps both within a single fleet or between fleets can be handled. The model maximises a the sum of total revenue of the flights flown minus the total costs of delays and the costs associated with cancellations.

Initially the Iterated Local Search (ILS) heuristic with a Variable Neighborhood Search (VNS) was implemented in order to be able to escape from local optima. The details of this implementation can be found in Løve and Sørensen [27]. Furthermore, the simple Steepest Ascent Local Search (SALS) heuristic was implemented as well as the repeated SALS (RSALS). The latter method functions exactly like the basic SALS heuristic but

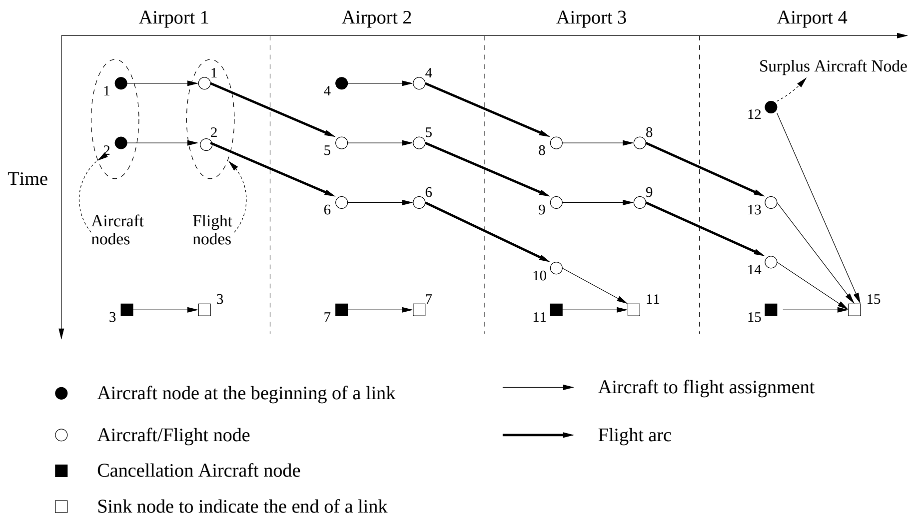


Figure 4: The network of the heuristic approach.

is repeated for various initial solutions. The initial testing surprisingly showed that the SALS heuristics were superior to the ILS heuristic.

A more in-depth description of the model developed and the results of the initial testing can be found in Løve et al. [28].

Experiments with a DAR solver based on constraint programming (CP) [20] were also done. Given a disruption, the CP-based DAR solver tries to obtain a feasible aircraft solution with minimal changes. Different types of changes (aircraft change within fleet, aircraft change outside fleet, cancellation etc.) can be associated with different "change points" and the objective is to find a solution with minimal change points. One attractive feature of the CP based DAR solver is, that it is also capable of finding all solutions with less than a specified number of change points. For larger instances, the performance of the CP based DAR solver was, however, less satisfactory.

### 5.3.2 DAR Experiments

Before any experiments were performed, the DAR constraints and costs were calibrated to reflect current decision-making policies within the Control Centre at BA. Basically, a number of disruption scenarios were prepared and analyzed with experienced aircraft controllers and the model parameter settings adjusted until DAR returned the types of solution options expected in all scenarios.

DAR can potentially be useful for different business purposes. Therefore the experiment was broken down into three fundamental components, to estimate the value of DAR for the following purposes:

- Real-time, on-line decision-support tool to aid effective recovery from schedule disruption on the day of operation.
- Support tool to aid schedule planners make effective, tactical schedule change decisions up to a few days before the day of operation.

- The decision-making core of a simulation tool capable of “flying” through a day of operation, thus allowing off-line investigation of the impact of different schedule design and/or delivery policies on schedule delivery key performance indicators.

**Experiment 1 – Evaluation of DAR as an on-line decision support tool for disruption recovery on the day of operation:** As DAR should be capable of solving any type of disruption to the aircraft schedule, the objective of this experiment was to compare the quality (and, to a lesser extent, response time) of solution options produced by DAR and by experienced aircraft controllers across a cross-section of realistic, stand-alone disruption scenarios ranging from very minor disruption to mass disruption at the hub airport.

As it was impossible technically to provide the aircraft schedulers with the drag-and-drop Gantt editing functionality of their live schedule editing tool in the experimental setting, they were required to solve disruptions using a static view of the schedule and no “playground” facility. This meant that it was significantly more difficult for controllers to solve disruptions in the experimental setting than in the real world and this is recognized in the experimental findings.

Five “medium-sized” disruption scenarios were prepared. Both the disruption scenarios and proposed solutions to those scenarios were specified by an experienced aircraft controller in advance and the scenarios were then run through DAR to compare the quality of DAR results with manual expectations.

The outcome of the experiment was, that the DAR was able to produce the same solution as the aircraft controller within at most two minutes compared to manual solution times of up to one hour. In addition, the DAR produced a number of other solutions, which were inferior in terms of the DAR objective, but which potentially could be better from the perspective of the crew resource or passengers.

**Experiment 2 – Evaluation of DAR as an on-line decision support tool for tactical schedule change prior to the day of operation:** As DAR should be capable of solving any type of real schedule change request received by Operations Scheduling, the objective of this experiment was to compare the quality (and, to a lesser extent, response time) of solution options produced by DAR and by an experienced aircraft scheduler, across a cross-section of realistic, tactical schedule change request scenarios. A set of 17 tactical schedule change requests and proposed solutions was created by an aircraft scheduler and these scenarios were then run through DAR to compare the quality of DAR results with manual expectations. The following types of schedule changes were considered:

- Insert extra activities into the aircraft schedule (e.g. charter flights, additional maintenance activities).
- Change duration of existing schedule activities (e.g. lengthen a maintenance activity).
- Complex cancellations (e.g. cancel an outbound and inbound leg where the legs are scheduled on different aircraft types).
- Move specified schedule activities to a specific aircraft type (e.g. upgrade particular

flight numbers to a 767 aircraft, move some maintenance from A320 to A319 aircraft etc.).

- Retime specific schedule activities to occur later than planned.
- Multiple change requests entailing combinations of the above types of request (e.g. add a new 757 charter, move some flying from 737 to A320, extend a maintenance activity on 737 etc.).

For simple change requests, DAR found the simple (and best) solutions that were also found by the scheduler. In more complex change requests where a solution option was not obvious to the scheduler, DAR again returned the types of option expected by the scheduler. Finally, the schedulers were particularly keen on the DAR functionality that allows them to restrict the types of options searched for by DAR. For example, schedulers can specify that DAR must not cancel or retime any activity or change certain, specified activities or aircraft at all (this is useful for protecting standby aircraft). If no good solution options are found by DAR then the schedulers would realize that some of the restrictions then need to be relaxed.

**Experiment 3 – Evaluation of DAR as the core of an operational simulation tool:** The capability to use a planned schedule and disruption probability distributions (or specific disruption events) as input and automatically simulate through a day(s) of operation is considered to be very powerful as it facilitates, in a safe environment, investigation into relationships between different schedule attributes and/or delivery policies and key performance indicators for schedule delivery. This, in turn, can help shape fundamental schedule design, management and delivery policies.

A simulation framework was built around DAR thus creating a tool which generates disruption events, invokes DAR to solve them, updates the schedule with the best DAR solution, generates more disruption events and so on. Rather than solving each single disruption in turn, DAR solves all disruption occurring during a specific time window (usually 1 hour) and then the simulation clock is advanced by an amount of time equal to the time window.

Prior to the DAR experiment, BA had already undertaken a manual "tabletop" exercise which comprised experimenters providing aircraft controllers with a snapshot of the planned aircraft schedule for a particular day and then "playing through" the day, informing the controller that the current time of day is now $x$, disruption $y$ has occurred and requires to be solved etc. The purpose of this manual exercise was to help estimate the impact that new types of schedules and different delivery policies are likely to have on various schedule delivery key performance indicators. It was decided to use this tabletop output as a manual benchmark with which to compare the output produced by DAR after simulating through exactly the same disruption events on exactly the same schedule.

The base experiment involved the entire BA 757 and A319 fleets. The result produced by the DAR had 30% lower costs, as defined by the agreed cost metric, than the manual benchmark. The solution reduced the number of cancellations from seven to five but increased total delay from 292 to 430 minutes. Cancellation of five or seven flights is rather extreme at BA and the reported saving may therefore not be representative for the typical day of operations. Other experiments, with other assumptions were also carried out.

These simulation runs verified the capability of the Descartes simulation framework to play through a day of operation successfully. In addition, they also demonstrated the value of DAR as an on-line, “hands-on” tool for Aircraft Controllers (i.e. using DAR to manage the tabletop day of operation rather than manual methods resulted in a significant disruption saving at the end of the day). The simulations do however not quantify the value of having a “What if?” simulation capability available at BA to evaluate various schedule creation, management and delivery policies and initiatives. The value of such a capability is clearly very difficult to quantify but some real applications within the business have already been identified (e.g. DAR is being used to aid an OR investigation into how the business could better plan and deliver international-domestic aircraft connections in the schedule).

### 5.3.3 DAR Conclusions

Firstly, the experiments demonstrate that, given a real schedule and realistic disruption situations, the DAR model recommends consistently the same recovery plan as the one suggested by an experienced aircraft controller. We believe, therefore, that the model contains all the correct business constraints and preferences and that the parameters governing the types of solution options generated (i.e. cost of delay, cost of cancellation etc.) have been calibrated correctly. There is some evidence in the stand-alone scenario experiments that DAR is capable also of identifying good potential recovery solutions that are difficult to spot manually, especially in situations of mass disruption, but it is difficult to quantify this accurately given the fact that controllers did not have available their usual schedule editing tools when creating manual solutions. More conclusive evidence that DAR is capable, in some situations, of identifying better solutions than can be found manually is found in the simulation experiment, although a direct comparison between manual tabletop and simulation results is difficult due to slight differences in the environment/rules. The capability of the mechanism to play through a day of operation, making valid recovery proposals at each decision-point has been demonstrated. Furthermore, there is obviously a business benefit in having this type of off-line simulation tool to aid policy evaluation etc. Some additional simulation runs have been carried out to demonstrate the capability to vary different parameters and observe the effect on schedule delivery key performance indicators (e.g. What if there were more/less standby aircraft available?, What if we were prepared to cancel flights more/less readily in disruption?, What if schedule stability was more important on the day of operation? etc.). Clearly, it is somewhat difficult to quantify the size of this business benefit financially.

## 5.4 Dedicated Crew Recovery Solver

The Dedicated Crew Recovery solver (DCR) was designed to be a useful decision support tool for Crew controllers and duty managers within Operations Control. The aim of the DCR was to use the available crew resource more effectively in a disruptive situation (i.e. to make better use of standby crew and improve re-assignment of disrupted crew members to alternative duties). The DCR was developed as a prototype tool in order to be able to prove the potential business benefit in building and implementing a crew recovery module. The development was iterative and was performed in close collaboration between the developers and the crew controllers within British Airways.

In the current, manual environment within British Airways, un-covered flights resulting from a disruption would usually be covered by crew members allocated from the pool of standby crew. However, the DCR provides functionality to re-allocate the disrupted crew members to alternative flights (with a later departure) whereas the flights subsequent to the disrupted flights will be crewed by the crew that has been de-allocated from the former flights. The re-allocation procedure is known as *re-linking* and is only possible within certain regulatory constraints. If re-linking is not feasible in the given situation, the delayed crew will usually be relieved from the duty and the subsequent flights operated by crew members called from standby duty.

The DCR developed during the Descartes project focused solely on the cabin crew resource and the rules and techniques used to manage these accordingly. However, the same methodology could easily be adjusted to manage disruption on flight crew also, as there is principally another rule set to build the model and parameters around. Furthermore, as the dimensions of the flight crew recovery problem are smaller than those of cabin crew, this means that being able to solve the latter also suggests that one should be able to solve the former problem.

### 5.4.1 Model and Methods

The DCR employs various techniques to generate recovery options. This includes re-linking, allocating crew from standby, up- and down-grading crew (i.e. for instance letting a standard cabin crew member work as a purser whenever appropriate) and pre-empting the problem (i.e. finding a solution in advance of the problem hitting the control centre). The solver uses a mix of these techniques to try to come up with structurally differing recovery options.

The DCR is based on a differential column-generation technique in order to find legal roster changes to each crew member involved in the disruption. The legal roster changes are included in a constrained integer optimisation problem (IP). The problem is then solved multiple times. For each option generated, an additional constraint forbidding the new option is added. This way, a sequence of options with increasing costs are found, which together constitute a set of best solution options. The ability to produce multiple recovery options is the real strength of the DCR as the controller can use his experience/intuition to pick the option best suited for implementation.

### 5.4.2 Experimental Results

The DCR was tested on a number of scenarios provided by the business team at British Airways. These scenarios were inspired by real, historic disruptions from the past.

A group of crew controllers were selected to produce manual solutions to the same scenarios as were used to test the DCR. After the tests the results were analyzed by an "expert user" in order to determine whether the solutions were feasible and realistic in an operational environment. The data that were used for the experiments were captured from the British Airways crew control systems prior to the experiment.

The Dedicated Crew Recovery solver was tested on a number of structurally different scenarios. One of these was the scenario described below. This scenario consisted of 5 delayed flights that were fed into the system simultaneously in order to evaluate the impact of the full scenario:

| Date | Flight | Origin | Destination | Departure | Arrival | Delay (mins.) |
|---|---|---|---|---|---|---|
| 12 AUG | BA-941 | DUS | LHR | 14:45 | 16:10 | 60 |
| 12 AUG | BA-970 | LHR | HAM | 13:20 | 14:55 | 90 |
| 12 AUG | BA-309 | CDG | LHR | 10:25 | 11:35 | 65 |
| 12 AUG | BA-393 | BRU | LHR | 10:50 | 12:00 | 110 |
| 12 AUG | BA-1446 | LHR | EDI | 13:00 | 14:15 | 60 |

A total of 21 crew members were involved in the delay scenario. The results below demonstrate how the Dedicated Crew Recovery tool solved this disruption. In this scenario, the flight delays caused conflicts in the continuing duties of the crew members involved. The primary problem was a violation of the minimum time required to connect from the delayed flight to the crew member's next flight. Generally, the minimum connection time rule is a hard constraint within the crewing rule set which under no circumstances can be broken.

The recovery option generated by the DCR involved standby crew from both the London Heathrow (LHR) central base station as well as the Glasgow (GLA) base. The breakdown of crew involved was as follows;

- 9 Crew used from standby duties
- 2 Crew used from standby duty who were Glasgow based, who were not originally part of the problem but were re-assigned from their original rostered duty to allow other permutations to occur.
- Upgrades of pursers to work as Customer Service Directors (CSD) positions and CSD's were removed from the trips.

The total recovery option involved 20 different flights and 30 crew members. This is a substantial increase to the number of flights and crew initially affected in the initial disruption. This is due to the fact that the DCR breaks up a number of the crew rosters in order to use these in the re-assignment of disrupted crew. However, this also underlines one of the drawbacks of the re-linking and re-allocation schemes used in the DCR; the solver does not minimise the number of disrupted crew. At British Airways, "the quality of life of the crew members" is considered to be very important and should be protected also in disruption, i.e. the recovery options produced should minimise the number crew members involved in the solution in order to protect the lifestyle of the crew members. The DCR, however, did use a greater number of crew in order to suggest a solution. A production quality version of the DCR should address this issue.

For the current scenario it was not possible to identify any specific savings with respect to the number of crew members needed to operate the disrupted schedule.

The rule sets by which the BA crew comply, are very restrictive in terms of what BA can and cannot do with the crew on the day of operation. Much emphasis is placed upon "crew quality of lifestyle", which means that limited changes are allowed. In order to make best use of a crew recovery tool within BA it would need to look at the possibilities of changing the cabin crew restrictions during unplanned operations. If BA were not to do this, then the benefits that would potentially come through manpower savings would be minimal. Capability to re-link crew could potentially save a number of standby crew on the day of operation, however, the current rule that states the crew member must be off duty no more a specified, short time later than their original planned arrival, restricts this greatly.

### 5.4.3 Conclusions

During the scope of the Descartes project, a prototype version of a dedicated crew solver was implemented. The DCR demonstrated that it provides the controllers with recovery opportunities in a disruptive situation that would not be able to be identified by manual means within an appropriate time frame. The prototype version of the DCR was tested within the context of "near real-life" data as the process of capturing real-time data turned out be very challenging as well as tedious.

The quality of the solutions produced by the DCR suggested that it needed some further development as most of the proposed recovery options were not ready to implement as they were and, in these cases, manual revisions were necessary. One of the reasons for this was that only a subset of the full set of crewing rules and regulatory requirements were taken into consideration when generating recovery options. However, given the full rule set and regulatory requirements, the DCR will provide the user with ready-to-implement options.

During the development of the DCR, a simulation study was performed in order to investigate the potential savings in standby usage offered by the re-linking technique. The study was based on 4000 different scenarios holding randomly generated, smaller disruptions in which an average of 10% of the flights were delayed with delays from 15 to 120 minutes. The initial findings suggested that the re-linking feature could generate substantial savings in cases of smaller disruptions.

Based upon the initial results it was concluded that the DCR would bring business benefit to the Operations Control environment and add value to the decisions made. By using this tool, Crew Controllers and Duty Managers could make more complex decisions in a shorter time, with savings due to better crew utilisation. However, the DCR developed within the Descartes project still needs some further work as it should be able to take the "quality of life" aspect into consideration when generating feasible recovery options. Furthermore, the options generated by the initial prototype did not take robustness into consideration, which means that further delays may make the proposed option inoperable. In a production environment, robustness should be considered when generating recovery options.

## 5.5 Integrated Recovery

Integration in the disruption management process can be handled in two fundamentally different ways: either by developing stand-alone tools for each of the relevant resources (crew, aircraft, and passengers) and then using these tools as components in an integrated system, or, alternatively, by designing and developing a system which determines solutions in an integrated fashion using concurrent access to the available information for each of the resources in question. The first system type is denoted Integrated Sequential Recovery (ISR), while the other will be called Tailored Integrated Recovery (TIRS).

ISR uses the subsystems for single resources as "black boxes" for solution generation and evaluation, hence the approach allows a stepwise development in terms of stand-alone systems for each of the resources. ISR therefore also allows the possibility of early business benefits based on single resource systems. Furthermore, it is not necessary to handle integrated information. Data for the subsystems may be handled independently for each subsystem e.g. for aircraft recovery problems, knowledge of the current crew situation is only necessary when a feasible solution from the aircraft point of view has to be evaluated with respect to crewing possibility. On the other hand, the process of steering the generation of solutions of high quality with respect to all resource areas is a challenge. The integrated recovery system must be able to control the dedicated solvers by putting very specific queries to them.

The potential advantage of TIRS is the ability to steer the solution process based on information on all resources in question. Ideally, this corresponds to having a mathematical model incorporating all resource areas rather than having one model for each resource area. Solutions generated in this way are generally expected to be better balanced across the different resource areas than solutions initially proposed because of their quality for one particular resource area. The tailored integrated approach faces two major problems: The data issue becomes much more complicated as aircraft, crew and passenger data must be integrated and the complexity of an integrated model virtually rules out the possibility of attacking the problem in a real-time setting based on optimal methods.

The core of ISR is an intelligent messaging system which integrates all available recovery subsystems. Integration is based on the principle of encapsulating each area's specific data and rules in dedicated recovery modules. Modules communicate by exchanging suggestions on schedule changes. Each dedicated recovery module is capable of evaluating the impact of a schedule change on its corresponding area of operations. Some modules are designed to generate schedule change suggestions, referred to as options. Currently, aircraft and crew recovery modules are able to suggest schedule changes to other subsystems. The challenge is to be able to generate options that are good from the overall business perspective. For this purpose, dedicated systems are designed to be able to consider constraints and objectives from other areas.

The development of TIRS is based on the so-called time-band network of Argüello et. al [5]. This is basically just a variant of the time-line networks used in many fleet assignment methods. In order to decrease the complexity of the problem, the time line is subdivided into intervals, which, together with schedule information, form the basis of the recovery method. This method has originally been developed in the context of aircraft recovery. The current TIRS-version builds a time-band network both with respect to aircraft and with respect to crew. A path in the aircraft network corresponds to the line of work of an aircraft and a path in the crew network corresponds to the line of work of a crew member. In the initial investigation, a full crew is considered as one unit. The basic idea is now, in case of a disruption, to represent a solution by a modified crew schedule and a modified aircraft schedule and to let the development of these two schedules take place concurrently. During the solution process, each schedule is therefore influenced not only by what is “good” in the context of aircraft with respect to crew, but also by the difference to that schedule, which is currently under consideration for the other resource.

Time-band networks for crew and aircraft are then constructed and a basic heuristic local search (based on simulated annealing) has been implemented. This is currently work in progress.

As mentioned previously, ISR and TIRS are two fundamentally different approaches to the generation of integrated solutions. The strength of ISR is that the generation of solutions to a disruption may come from any subsystem. All generated solutions are evaluated by each of the single resource systems, in order to get an over-all evaluation taking into account all perspectives. However, if only single resources are used for solution generation, ISR might risk generating solutions that are of a high quality in most areas and of very low quality for the others, may be generated. This is due to the fact that each resource area focuses on the cost related to that particular area.

Generating solutions of good quality across all resources is the underlying idea of TIRS. Here, one should not expect solutions of very high quality for one resource unless the solution is also of acceptable quality for the other resources. As indicated, such an approach depends on concurrent access to data from all relevant resources as well as a common representation of the schedule across all resources. Therefore, the approach is an order of magnitude more complex than the ISR approach.

However, if the approach turns out to be successful, a TIRS system may be a valuable component in an ISR system. On the other hand, a TIRS system may be used to solve single resource problem by (based on user input) “ignoring” all other resources during the solution process.

During the Descartes project integrated recovery was an active research issue but no results was obtained.

# 6 Conclusions and further work

In reality, an Operations Control Centre is required to make important operational decisions with big potential operational and commercial ramifications, often under extreme time pressure and sometimes without complete information on the situation in hand. Using manual approaches, this often means that only one or two possible solution options may be considered hence there is a real risk that a solution that is far from optimal across all the key areas may be implemented. Furthermore as a result of the sequential nature of the manual process decisions implemented for one resource might very well have a profound impact on other areas.

The research for IT-supported decision support tools is mainly characterized by single resource systems and a rather academic approach. The Descartes project is among the first approaches to develop a system spanning multiple resources including integration with data sources. It was demonstrated that the system improves the quality of decision making. The focus of the system is not to generate the optimum solution in the strict academic sense, but rather to provide flexible tools which can add value to the business process of operations control at various airlines.

The process of operations control is similar to management of any complex system. The essence of it is to ”manage the mess”. In order to quantify how much the result improves due to introduction of a new system, one has to implement a thorough and detailed accounting methodology. Moreover, this methodology has to be in place sufficient time prior to introduction of a new system.

Whilst it seems that intelligent decision-support certainly has a role to play in helping operations make more considered, informed decisions during disruptions of all types and severities, there are, of course, a host of practical challenges, not least of which is the "real-time" operational environment itself. In such an environment, where the situation is often changing rapidly, the data management capability of decision-support systems can be at least as big a challenge as the actual problem-solving. Automatic decision support has significantly higher requirements on data quality than traditional methods. Also, airline system architectures has to grow to a new level to exploit new possibilities provided by this technology. In particular, the ability to provide access to real time data and the ability to receive on line changes has to be significantly improved in the current system architectures to meet the new challenges.

It is a fiction that a complex process, like operations control, of a large organization, like an airline, can be improved by installing a magic new IT system. The reality is that the improvement process has to start with Business Process Redesign (BPR) and the corresponding IT project should commence only when the ground for it is ready.

Furthermore, the complexity of hard airline business rules (eg crew and aircraft maintenance rules) and the multitude of "soft" rules that exist in practice mean that, whilst decision-support tools can definitely present users with potential, good quality solution options, the intricacies of the operational environment certainly call for manual sense-checking and the application of "local knowledge" to any suggested options.

One interesting application of the integrated toolset presented here is in contingency planning for medium/mass disruption. By using the tools to score each flight legs in terms of its attractiveness for cancellation from both a commercial and operational perspective, effective contingency plans can be produced in advance. As the need for sophisticated, real-time data management capability is also eliminated, this is a practical, "quick-win" potential use of decision-support.

In conclusion, as large airlines invest considerable time and resource in developing and managing the schedule carefully throughout its lifetime, it obviously makes sense to deliver this "optimal" schedule as far as possible. When disruption is encountered on the day of operations, however, there can be a tendency to migrate away from this carefully planned schedule as a "firefighting" mode is adopted. As the full ramifications of changing large parts of the schedule are extremely difficult to predict, especially at heavily congested, constrained airports like London Heathrow, schedule stability is a key consideration. Any support that helps an airline deliver the planned schedule and, in times of disruption, return to plan as effectively as possible, is therefore very attractive.

On the way to promote automatic decision support, and to make it as wide spread and commonly accepted as, for example, pairing optimization we see three main challenges: quantify business value, improve data quality and system accessibility and combine IT and BPR projects.

Interesting research directions closely associated to disruption management is simulation and robust planning. Simulation allows users to get a better overview of the operational impact before the airline commits itself to a change of plans, as well as a more quantitative approach to evaluating possible recovery scenarios.

In robust planning, parts of the "operational responsibility" is placed in the planning process. The objective in robust planning is not only to minimize cost but also to build schedules that are capable of absorbing minor disruptions and allow for efficient recovery. Research in this direction is starting to appear in the journals (see eg. [1, 43, 18]).

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