Chapter 10 Airline Scheduling and Disruption Management[*]

Cheng-Lung Wu and Stephen J. Maher[†]

Learning outcomes:

- To understand the principles of airline scheduling including the four main stages of scheduling: schedule generation, fleet assignment, aircraft routing, and crew rostering.

- To understand the mathematical concepts behind each component of scheduling.

- To appreciate the complexity of airline scheduling and schedule optimisation.

- To recognise the role of operational uncertainties and their impact on airline operations and scheduling.

- To identify options in airline recovery and disruption management.

- To understand the future trends of airline scheduling including integrated scheduling and robust scheduling.

11.0 Introduction

This chapter focuses on airline schedule planning and includes the following topics: airline scheduling (procedures and methods), airline operations, disruption management, and schedule recovery. On the topic of airline scheduling, this chapter introduces the major elements of scheduling and whenever necessary, mathematical models are also introduced. For airline operations, this chapter covers operational uncertainties and highlights the influence of scheduling practices on managing

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schedule operations in the industry. Disruption management by modern airlines is introduced to demonstrate how schedule disruptions may occur, how airline schedules are recovered, and how disruption management can inform schedule planning through feedback. Readers should note that although we may have addressed each topic within the limited space of this chapter, each topic itself contains a vast literature that is worth further study and self-exploration.

11.1 Airline schedule planning and resource utilisation

Tasks in schedule planning

The task of airline schedule planning is essentially equivalent to resource allocation and management with a strong focus on the optimisation of resource utilisation. Airline schedule planning comprises four main tasks, which are often conducted sequentially in the industry, namely: schedule generation, fleet assignment, aircraft routing, and crew rostering (Wu, 2010). The schedule generation process aims at designing a timetable that is competitive in the market (in terms of departure times, frequency of flights, and the chosen departure/arrival airports), and is also able to meet potential travel demands. With the draft timetable, the task of fleet assignment is to determine which type of aircraft should be used to fly a particular sector so potential revenues can be maximised for an airline.

Keyword: Sector – a sector (also known as a 'route' in the industry) is a flight path that connects two airports: the origin airport and the destination airport (an O-D pair). The development of a new service between two airports is hence called 'route development' in the industry.

According to fleet assignment results, aircraft are then assigned to fly certain sectors depending on the fleet type and maintenance requirements of individual aircraft. With the timetable and aircraft assignment ready, the task of crew scheduling is to assign individual crewmembers to various flying duties that comprise a number of sectors. The goal of crew scheduling, apart from satisfying the legal requirements of crew skill levels and minimum crew sizes for each aircraft type, is to minimise crewing

expenses because this cost item is often the second largest cost (only after the fuel cost) among all cost items of running an airline business (Doganis, 1991).

Resource utilisation

Resource utilisation is the ultimate goal of airline scheduling. This is due to the fact that aircraft are expensive assets and airline crew (in particular pilots) are highly skilled and expensive to employ. A narrow body aircraft, such as Boeing B737, can cost around US$100-150 million, while a jumbo jet, such as Airbus A380, can cost around US$400-450 million depending on the market. Airline crew require specific training to conduct different duties. In particular, pilot training is costly and time-consuming. Hence, the cost of hiring a senior captain is high.

Depending on employment conditions and countries, an A380 captain can have a compensation package worth more than US$250,000 per annum. The net profit margin of global airlines according to IATA (2014b) is about 2.4% in 2014. Hence, cost cutting and resource utilisation strongly influences airline scheduling. The desire of resource utilisation is also reflected in the pursuit of schedule optimisation by adopting mathematical models that assist in optimising various tasks of airline scheduling. Models have also been adopted on the commercial side of the airline business to aid tasks such as revenue management and demand forecasts.

A connected network with resource synchronisation

A critical element in airline scheduling is the synchronisation of resources in an airline network (Wu, 2010; p124). In the context of airline scheduling, *synchronisation* means the pairing or matching of two or more resources that cannot operate independently. For a given timetable, different fleets are assigned to flights. The results of fleet assignment are then *matched* with routings in aircraft route planning that aims to *synchronise* flights with individual aircraft in the form of *routings*. Crew are then *paired* with those routings to minimise crewing costs. Rosters for individual crewmembers are then synchronised with those paired flights (called *crew pairings*) as well as aircraft routings. During flight operations,

synchronisation also extends to passenger itineraries that *pair* with various flights in the network.

Keyword: Routing – a routing is a series of connected flights that are assigned to be conducted by a single aircraft.

Given the nature of resource synchronisation and the pursuit of optimisation, the task of airline scheduling becomes extremely complex for modern airlines. It is exactly because of this desired synchronisation and the benefit of cost minimisation (and profit maximisation), planning stage efficiency takes a focus at the expense of operational performance. *Over* optimisation in the scheduling process can make disruption management of daily airline operations a very daunting task, depending on the nature and scale of disruptions. Mathematical models are used to better plan for disruptions in airline scheduling and for disruption recovery. Some key models will be introduced in this chapter to assist in the understanding of the science in schedule optimisation.

11.2 Flight schedule generation and travel demand

Travel demand

Travel demand is uncertain, although in general travel demand is highly correlated with the regional and global economy (Boeing, 2014; IATA, 2014a). Airlines publish their flight schedules one season in advance, so that short-term travel demand forecasts also follow the nature of seasonality. Mid-term or long-term travel demand forecasts are mostly for route development and fleet planning purposes, and may contain higher levels of forecast errors.

Travel demands of individual sectors are of high interests to airlines. The aim of flight schedule generation is to build a schedule that is appealing to potential travellers, while balancing the limited availability of the airline's aircraft capacity. The travel purpose of a passenger can influence the preference of flight choices and this in turn determines the demand for a particular sector. Business travellers tend to

leave early in the morning and return in the evening for domestic trips, whereas leisure travellers are more flexible with departure times and often seek cheaper tickets. Therefore, airlines tend to cater flights more for business travellers during their preferred travel hours and charge a premium for those flights. These flights have higher ticket prices, attract more business travellers, and depart during morning and evening peak hours. In contrast, flights scheduled during off-peak hours tend to be cheaper and use smaller aircraft, aimed at attracting more leisure or less time-sensitive passengers.

Schedule generation (timetabling)

Apart from determining the departure times of flights between an O-D pair, the other critical element in schedule generation is to determine the flight frequency for each sector. The 'rule-of-thumb' in determining flight frequency in the industry is that the higher the frequency of a sector, the more appealing this airline (and its flights) would be to travellers, especially for business passengers. This is primarily about market share; the higher the market exposure, the higher the likelihood of achieving a bigger market share. Flight frequency can be empirically calculated by:

$$frequency = \frac{D_{ij}}{C_k \cdot \rho}$$

$$(1)$$

Where D_{ij} is the forecast demand between airport i and j; C_k is the capacity of fleet type k; ρ is the assumed seat factor of the sector (often set between 75% and 80%).

Case Study: Larger aircraft with lower frequency or smaller aircraft with higher frequency?

In a hypothetical situation, the demand for travel between Sydney and Hong Kong is 1,000 passengers per day, both directions. An airline owns a few fleets including A380 (500 seats), A330 (280 seats), and B787 (240 seats). When A380 is used, the frequency between SYD-HKG is one per day per direction. A330 can do two flights per day, offering 560 seats each way and if B787 is chosen, the frequency can be

lifted to three services per day each way (offering 720 seats in total). Then, how frequent should the airline fly the SYD-HKG sector and with which fleet?

This question has no fixed answer. The answer heavily depends on the scheduling strategy of the airline and the limitations of the fleet size (please refer to '*Fleet assignment*' in the next section). Assuming all three fleets are available to operate the SYD-HKG sector, the use of A380 offers economies of scale by conducting a single flight to meet demands. Hence, the unit cost is possibly the lowest and profits can be higher.

The strategy of offering a daily A380 service is to 'consolidate' demand into one flight and operate an efficient aircraft for such a trunk route. The low frequency may limit passengers' choices in terms of departure times during any booking day. Often, this type of strategy is used by an airline to 'feed' traffic to a destination hub airport, HKG. Inbound traffic is then fed to a partner airline based at HKG, which can provide services to other destinations beyond HKG (often through code-sharing). This is how Qantas and Cathay Pacific currently work within the scope of One World Alliance for the SYD-HKG sector such as SYD-HKG-TPE.

If smaller aircraft are used, the airline can offer a higher frequency for this sector; A330 and B787 can offer two and three flights per day respectively. This strategy maximises the potential market share due to higher 'exposure' to the market, and is also more convenient for passengers in choosing departure times; ideal to cover both leisure passengers who are less time sensitive and more cost sensitive, and business travellers who are more time-sensitive in choosing departure/arrival times. This is the current strategy Cathay Pacific has chosen to compete with Qantas on the SYD-HKG route by offering four services per day using A333 and B77W. Air New Zealand also employs a similar strategy for its Asia-bound flights.

Schedule generation is often done well in advance, about 8-10 months before a new season. There are on-going schedule improvements and modifications after this draft timetable is passed on to other departments of an airline. The timetable is often published early by airlines, so passengers can make travel arrangements early (a.k.a.

early-bird bookings). However, the core travel bookings only start to appear three months before the departure date of a particular flight.

Keyword: Schedule Generation – also known as timetabling. This is a process where an airline tries to use limited aircraft capacity to meet travel demands while staying competitive in the travel market.

Keyword: Season – there are two 'seasons' in airline scheduling, known as the Northern Summer Season (April-September) and the Northern Winter Season (October to March).

11.3 Fleet assignment and aircraft routing

Fleet assignment

After a timetable is drafted, an airline needs to allocate its available aircraft capacity to meet the potential demands, which are based on forecasts and mostly uncertain in nature. By using fleets with different sizes, the flight frequency can be adjusted in order to vary the supply of aircraft capacity in an airline network. Large aircraft are often used on *trunk routes* with a lower frequency where the traffic volume is large, while narrow body aircraft are deployed where the volume is 'thinner' or where frequency is more valuable in the market. Hence, the task of fleet assignment is to match uncertain demands with a *fixed* supply of aircraft capacity, and to maximise potential profits. The uncertainty of demand and limited aircraft capacity makes the fleet assignment an inherently challenging problem.

Case Study: What is the optimal fleet assignment?

In a hypothetical case, the demand forecast of a sector is 220 passengers per day per direction. Since demand is uncertain, the demand forecast is best represented as a stochastic variable, say following a Normal distribution with mean value of 220

passengers and a standard deviation of 25 passengers, i.e. $N(220,25)$. The airline has two fleets: B737 (180 seats) and B787 (240 seats). In a fleet assignment exercise, if the airline chooses to use B737 to service the sector, then demand will 'spill'; on average, 40 passengers will be turned away because the flight is often fully booked. If the airline chooses to use B787, then there will be no demand spill, but the average seat factor will be 92% with occasional booking spill. So, which choice is the optimal fleet assignment for this airline?

The fleet assignment problem must be approached from a holistic view. The operating cost of a large aircraft is higher and the use of B787 in this case risks the airline with a lower seat factor (less revenues) compared with using B737. B737 has lower operating costs with a higher seat factor (because supply is lower than demand for this sector), so the airline can expect higher yields by charging more. However, the cost of passenger spill (i.e. loss of potential revenues) when choosing B737 adds to the operating costs when evaluating this fleet assignment problem for this particular sector.

For the whole network, the decision in fleet assignment is to assign the optimal fleet type to each sector by maximising the total profits or minimising the total costs of operating a schedule. Hence, the optimal choice of fleet for our hypothetical case can be B737 or B787, depending on the result of the whole fleet assignment problem. Assigning B787 to this sector may seem to be a suboptimal choice, but this choice may still turn out to be the optimal decision for the whole network.

Technically, the Fleet Assignment Model (a.k.a FAM in the industry) is often formulated as an integer program that aims to minimise the operating costs of the network (thereby maximising profits) as shown in Eq(2).

$$\min C = \sum_{j \in J} \sum_{i \in F} c_{i,j} x_{i,j}$$

(2)

where C represents the total operating costs of the network; $c_{i,j}$ is the total operating costs if flight i is assigned to fleet type j; $x_{i,j}$ is the binary decision variable of assigning flight i to fleet j. The total operating costs, $c_{i,j}$ include the physical

operating cost of flying sector *i-j*, the expected spill cost of adopting fleet *j*, and the recapture (offsetting the spill costs) of this sector due to adopting fleet *j*.

There are three sets of constraints when optimising FAM: 1) flight coverage: each flight must be assigned to only one fleet type; 2) aircraft flow balance: the total number of inbound aircraft at an airport at any particular time must equal to the total number of outbound aircraft plus any other aircraft left waiting on the ground; and 3) fleet size: the number of aircraft used in the solution must be less than or equal to the total fleet size.

Keyword: Fleet Assignment – is the optimisation process that aims at maximising potential revenues by optimally allocating different fleets of aircraft to conduct flights at different levels of demand.

Keyword: Spill – is the situation when a passenger wants to book a particular flight but cannot get a ticket due to various reasons. When this happens, this passenger is 'spilled' and this represents a loss of revenue for an airline if the passenger buys a ticket from another airline.

Keyword: Recapture – if a spilled passenger then chooses to buy a more expensive ticket of the same flight (same airline) or change departure time/date, and still stay with the same airline, then this passenger is 'recaptured'; there is no revenue loss for the airline. Hence, the higher the frequency of a sector, the higher the recapture rate.

Aircraft routing

The solution of FAM partitions the flight schedule into sub-timetables, one for each fleet. An Aircraft Routing (AR) problem is then solved on each of these sub-timetables to connect flights into routings. There are two main objectives of the aircraft routing problem: 1) flow balance: the arrival airport for a flight by an aircraft must be the departure airport for the subsequent flight by the same aircraft; and 2) flight coverage: each flight must be covered exactly once in AR.

The AR problem is an important component of the sequential planning process. A modified form of this problem also appears in the operational stages. As such, details of the AR problem are presented here to aid the discussion of models presented later in this chapter. The flight partition related to fleet f is denoted by N^f, with each contained flight indexed by j. Since the objective of this problem is to identify a set of aircraft routings, each decision variable (y_p) identifies a feasible routing. The set of all feasible routings for fleet f is given by P^f and indexed by p. The parameters a_{jp} equal 1 to identify whether flight $j \in N^f$ is contained in routing $p \in P^f$. The aircraft routing problem is given by Eq(3):

$$\min \sum_{p\in P} c_p y_p \tag{3}$$

$$\text{subject to} \sum_{p\in P} a_{jp} y_p = 1 \forall j \in N^f,$$

$$y_p \in \{0,1\} \forall p \in P^f$$

Since all aircraft are of the same fleet for each individual aircraft routing model, the cost of flying each aircraft is almost identical. However, there are alternative costs that can be used in the objective function to achieve different optimisation goals. For example, the objective function can be: minimising the 'cost' of routing (if certain flight connections are cheaper or more expensive, e.g. through flights are desired but connections with long transfer times are not), or minimising the 'usage' of aircraft by creating 'tight' connections to reduce aircraft ground times. It is also possible to set $c_p = 0, \forall p \in P$ and solve this problem as a feasibility problem. However, it could still be advantageous to set c_p to some small costs to ensure the number of selected routes, given by $y_p = 1$, is minimised. The first set of constraints ensures that each flight within the schedule partition for fleet f is assigned to exactly one aircraft. Finally, the aircraft routing variables (y_p) are binary, i.e. they can only take the values 0 (not selected in the final solution) or 1 (selected in the final solution).

The above formulation assumes that all routings are known *a priori*, which is generally not possible for real-world problems. Even for modest flight schedules, the number of potential routings can be in the order of billions. Enumerating all routings is computationally difficult and, even if possible, the resulting AR problem would be

intractable. This is commonly addressed by generating only a subset of all routings by using a heuristic method or employing the solution technique of column generation (Barnhart et al., 1998; Desaulniers et al., 2005).

The output of the AR model are routings for a particular fleet. An example of a domestic B737 routing for a one-day duty in Australia is as follows: FLT025 (SYD-BNE) — FLT026 (BNE-SYD) — FLT085 (SYD-CNS) — FLT076 (CNS-BNE) — FLT046 (BNE-MEL). The aircraft overnights at Melbourne (MEL) after finishing the routing. Routings in international operations tend to be longer and may span over a few days, depending on the sector length of international flights.

AR is commonly performed two to three months in advance of operations. Then the results are passed on to the crew planning team for crew scheduling. Readers should note that routings are specific to a particular fleet, but not to any specific aircraft in the fleet. The job of assigning a routing to a particular aircraft for operation on a particular day is called Aircraft Tail Assignment.

Aircraft tail assignment

Each aircraft has a *tail number*, which is literally the ID number of an aircraft. When generic routings are assigned to individual aircraft, tail numbers are used to identify each aircraft and its routing assignments; hence, this task is called Tail Assignment (TA) in the industry.

The objective of TA is to assign candidate routings from AR to each individual aircraft and also meet the major requirement of TA: aircraft maintenance. Depending on the usage of an aircraft, various maintenance activities are scheduled to maintain aircraft worthiness and meet legal safety requirements of local aviation authorities. Major maintenance, e.g. C and D checks can take months to finish and require an aircraft to be taken off service. Minor and regular services usually take around eight to ten hours e.g. A checks can be performed overnight at a maintenance base. Some maintenance tasks are due by calendar days, while others are required by cycles such as servicing the landing gear system.

In TA, schedulers need to take into account the maintenance history of individual aircraft leading to the need for a maintenance slot at a maintenance base, and also the projected maintenance activities that need to be carried out over the next one or two months. Then the task of TA is to assign routings to specific aircraft so the aircraft can arrive at a specific maintenance base at the right time, and ideally with some buffer times in the routing schedule.

The challenge in TA is that if there is no option to route an aircraft to a maintenance base before a key maintenance task is due, then either the routings must be modified (revising the solution of AR), or the aircraft must be taken off service because it is not able to meet maintenance requirements. Not being able to route an aircraft to a service base in time can be very costly to an airline. However, if an aircraft is brought to a maintenance base too early, then valuable aircraft time is 'wasted' and the aircraft may receive excessive maintenance than needed over the lifespan of an aircraft. This early maintenance is also costly to an airline.

Case study: How much buffer should we plan in TA?

Compare the following three hypothetical TA routings and identify the optimal TA choice:

R1: FLT025 (SYD-BNE) — FLT026 (BNE-SYD) — FLT085 (SYD-CNS) — FLT076 (CNS-BNE) — FLT046 (BNE-MEL), arriving in Melbourne at 10PM for a scheduled A check from 11PM to 7AM the next day.

R2: FLT025 (SYD-BNE) — FLT026 (BNE-SYD) — FLT085 (SYD-CNS) — FLT120 (CNS-MEL), arriving in Melbourne at 4PM for a scheduled A check from 11PM to 7AM the next day.

R3: FLT025 (SYD-BNE) — FLT026 (BNE-SYD) — FLT090 (SYD-MEL), arriving in Melbourne at 2PM for a scheduled A check from 11PM to 7AM the next day.

The optimal TA choice for most people may be R1, because the aircraft arrives at MEL just in time for the A check; no waste of aircraft time for operations. However,

schedulers may opt for R2 or even R3 instead of R1 because if any delays happen to earlier flights in R1 during the day of operation, then the arrival in MEL may be delayed. For a late arrival to the maintenance hanger, the available maintenance time is shortened, causing maintenance tasks to be delayed or be 'skipped' to the next maintenance opportunity. If critical maintenance tasks cannot be finished in time during the planned maintenance slot, it may potentially delay the morning operation the next day in MEL or even disrupt other maintenance tasks in MEL that require the hanger space.

However, bringing the aircraft back to base earlier can also be costly. R3 contains two flights less than R1 and may put the aircraft idle on the ground in MEL for nine hours before starting maintenance. This idle time can be seen as schedule buffer time in TA with an opportunity cost that could have been used to earn extra revenues. So, which choice would you make?

Apart from maintenance requirements, some airlines also require aircraft to experience balanced wear and tear from different operating conditions, such as weather and landing cycles. Too much exposure to extreme (cold/hot) weather conditions may cause certain parts of an aircraft to wear more quickly, and hence require more frequent maintenance (costly). Other operating conditions such as short sector lengths (i.e. short flights) with a high number of landing cycles may push the airline to service certain parts of an aircraft more often, e.g. landing gears. Hence, schedulers *rotate* routings among aircraft in TA, so over a long period of time, (e.g. one year) each aircraft can equally go through most, if not all, operating environments to balance the wear and tear among aircraft.

Keyword: Cycle – a cycle is a complete taking off and landing operation by an aircraft.

11.4 Airline Crewing

Crew pairing

After AR, flights are now *synchronised* with aircraft. The task of crew planning is then to design a crewing schedule that is able to match crewing requirements of different fleets with routings from AR. Typically in the industry, the airline crewing problem is broken down into two sub-problems, namely Crew Pairing (CP) and Crew Rostering (CR). CP is conducted first and the outputs of CP (called 'pairings') are used in CR for building rosters for individual crewmembers.

Pairings must meet the requirements of safe operation of aircraft by crew. Most countries have legal requirements for the crewing of aircraft. Typically, these sorts of legal requirements are mandated to regulate the working hours of pilots for fatigue management purposes. For instance, the so-called '8-in-24 rule' mandates that a pilot cannot fly more than eight hours within any 24-hour period (Barnhart et al., 2003). In addition to legal mandates, crew bargaining agreements (if applicable) between an airline and its crew unions also impose further conditions on crewing and are at least equal to and, for most cases, stricter than those conditions imposed by government authorities. For instance, the cap imposed by many aviation authorities on the total flying hours of a pilot per annum is about 1,000 hours, but many crew bargaining agreements adopted by western airlines impose an 800-hr yearly cap; a productivity reduction (hence, cost increase to airline businesses) by at least 20%.

Keyword: Pairing – a.k.a 'a tour of duties', is a series of flights that are: 1) connected for a single crewmember to conduct, 2) starts from a crew base and ends at the same crew base, and 3) meets crewing conditions. A pairing can span over multiple days but often capped with a maximum 'time away from home'. A typical domestic pairing spans for a few days, while an international pairing may last more than a week, depending on flight networks and crewing conditions.

Since crewing is, for most airlines, the second most expensive cost item (only after fuel costs) for running an airline business (Doganis, 1991), minimising pairing costs is of paramount importance for airline profitability. Given the complex crewing conditions and potential choices in building pairings, CP has become a difficult problem – a challenging mathematical problem indeed. Integer programs are

developed for CP to minimise crewing costs, and a typical model form is shown by Eq(4):

$$\min C = \sum_{j \in P} c_j x_j$$

(4)

where c_j is the cost of choosing pairing x_j, among all possible pairing candidates in set $P(\forall j \in P)$. The only set of constraints for this CP model is the flight coverage in which each flight must be 'covered' only once in the pairing result. This model form is elegant with few constraints. However, the set of potential candidate pairings, $P(\forall j \in P)$, can grow exponentially when a network gets larger and more complex. Techniques such as the column generation method (Barnhart et al., 1998; Desaulniers et al., 2005) are adopted to efficiently generate good pairing candidates during the iterations of solving the CP problem to optimality (see Chebalov et al., 2006; Klabjan et al., 2002; Schaefer et al., 2005 for some examples).

Case study: How long should a pairing be? The shorter, the better?

Compare these three hypothetical pairings for pilots (based at PVG):

P1: {Day-1: (PVG-TPE) – (TPE-PVG) – (PVG-SIN)}– <overnight@SIN>–{Day-2: (SIN-PVG) – (PVG-ICN) – (ICN-PVG)}; flying hours: 8 hours on day-1 and 8 hours on day-2.

P2: {Day-1: (PVG-TPE) – (TPE-PVG) – (PVG-HKG) – (HKG-PVG)}; flying hours: 7 hours on day-1.

P3: {Day-1: (PVG-TPE) – (TPE-PVG)}; flying hours: 3 hours on day-1.

All three pairings start and finish at the base (PVG, Shanghai Pudong International Airport) and are legal pairings. P1 is a two-day pairing with an overnight for pilots at Singapore, while P2 and P3 are both one-day pairings. From the viewpoint of crew productivity with the imposed 8-in-24 rule, P1 is the most productive and efficient pairing. P2 is less productive, while P3 is the least productive with less flying hours. So, which one is better?

Let's look at this question from the 'cost' perspective. For one-day pairings such as P2 and P3, the cost of crewing is mostly from flying hours. Hence, it's ideal to get these pairings as long as possible to the daily flying-hour cap, 8 hours. P2 is clearly superior to P3. Then, isn't P1 the best option because it is both long and runs to the daily hour cap for both days of the pairing?

Apart from the costs of flying hours, the cost of P1 also contains the overnight expenses of crew at Singapore including hotel, ground transport to/from the airport and also living allowances. These expenses (in particular, accommodation costs) can easily add up to a huge amount of crewing costs that actually motivated some airlines in the 1980s and 1990s to run their own hotel chains.

From the cost minimisation perspective, P1 is more expensive than the combination of two P2-type pairings (if feasible), so it is a better choice to break down P1 and replace it with two P2-type one-day pairings. However, this is not always feasible in pairing optimisation because some flight times are longer than others and it is not always possible to bring crew back to base on the same day.

For crew salaries, many airlines pay crew not only by flying hours, but also by *credit hours*. In doing so, an airline pays a *premium* for each pairing depending on how many *synthetic hours* are included in each pairing; the more synthetic hours, the higher the premium and the more expensive a pairing becomes.

Keyword: Credit hours – is the total number of 'pay hours' that a crewmember may be compensated. Apart from the flying times, credit hours generally include sign on/off times, turn-time in between flights, and rest times (if any) within a duty day of a pairing. Hence, the credit hour is always longer than the flying hour for any pairing.

Keyword: Premium – is the extra cost that an airline pays crew for conducting duties. Premium is calculated as the percentage of the hour difference between credit hours and actual flying hours compared with the flying hours alone.

Case study: Pairing cost calculation – the impact of premium

Following on the previous case study pairings, we now calculate the cost of each pairing by only considering the following three cost elements: flying time ($100/hr for pilots and $50/hr for crew), non-flying time ($25/hr for all crew), and overnight hotel costs. We calculate the costs of pairings in the context of A320 operations with two pilots and four cabin crew.

To simplify the calculation, all turnarounds between flights are assumed to take one hour and the sign on/off times before starting and finishing a daily duty is one hour in total. For a set of six crewmembers for A320 operations, six hotel rooms are required per night at Singapore (assuming no room sharing), costing US$1,200 per night. If this particular flight has a daily frequency between PVG and SIN, then the total accommodation bill for the crew of the PVG-SIN flight to the airline is about US$438,000 for this particular flight alone; nearly half a million dollars! The cost breakdown of each pairing is provided in Table 1.

Table 1. Cost comparison of case study pairings

	Flying	Non-flying	Hotel	Total Costs	Premium
P1	$6,400	$900	$1,200	$8,500	38%
P2	$2,800	$600	$0	$3,400	57%
P3	$1,200	$300	$0	$1,500	67%

From a cost perspective, P1 is the most expensive choice and P3 is the least expensive. However, from a premium perspective, P3 is the least 'efficient' pairing (67% premium) because the flying time (3 hrs) is relatively short when compared with non-flying time (2 hrs). On the contrary, P1 is the most efficient pairing with a 38% premium only. Typically, airlines prefer pairings with low premiums because these pairings end up cheaper (without paying for excessive synthetic hours).

High premiums are unavoidable especially for networks that have many short sectors. While an airline can utilise a narrow-body jet, e.g. B737 for 12 hours during a day, a crew pairing can only cover half of the aircraft routing. Adding up the turnaround times between flights of a domestic pairing cause the premium to increase; domestic

pairings typically have premiums ranging between 45% and 65%. In contrast, long-haul flights tend to have longer flight times, so premiums are typically low, ranging between 15% and 30%.

For instance, the premium of the SYD-SIN sector (eight-hour flight with one-hour sign on/off times) is only 12.5%, which is a very efficient pairing. However, if the same flight time is broken down into a return trip between Sydney and Perth with a one-hour turnaround in between, then the premium increases to 25%! The rule of thumb in CP optimisation is to look for low premium pairings that collectively achieve the lowest crewing costs. However, the optimisation result is likely to contain some good (and long) pairings as well as some high-premium and short pairings in order to cover the whole network. This is unavoidable.

The outputs from CP are lists of pairings for each fleet type. Some pairings are fleet specific, e.g. pairings for A320 pilots, while some pairings can be more flexible for cabin crew such as pairings for A320 and A319. Regulation mandates that a pilot can hold only one aircraft type certification at any one time, so an A330 pilot can only be scheduled to fly A330 and not A320, even though the A330 pilot may have flown A320 and held a certification before. However, if a cabin crew is 'cross-trained' for both A319 and A320, then this crew can accept duties from both fleets. Cabin crew cross-training can increase crewing flexibility and reduce crewing costs, although the training itself will cost the airline.

Crew rostering

It is noted that crew pairings are 'anonymous' and not crewmember specific, but fleet type specific. Therefore, in terms of resources synchronisation, crew is now synchronised with aircraft (AR) and flights (FAM). The task of assigning pairings to individual members of the crew is called Crew Rostering (CR). The goal of rostering is to ensure that the employment conditions of crew are met including training days, annual leave entitlements and *ad hoc* leave requests, flying duties (and annual hour caps), and non-flying duties (such as stand-by duties). The other key aspect of CR is to ensure that each flight (by a particular fleet type) has enough crew aboard with an adequate skill mix. A common composition of a crew set for a narrow body jet

aircraft such as A320 includes: one captain, one first-officer, one cabin manager, and another three cabin crew. If this is the minimum crew set and skill combination for A320, then the goal of CR is to ensure that all flights by A320s have enough crew with the right skill mix to conduct all flying duties.

Keyword: Airline Crewing – is the task of assigning crewmembers to individual flights so the skill requirements and crew size for a particular aircraft are legally met.

Rostering conditions can be complex. Often in the industry, crew bargaining agreements further impose specific crewing conditions such as the maximum duty day per week (per seven days), days off in between duties, rest days after duties that cross the International Date Line or time zones, and a minimum guaranteed number of working hours per roster period … etc. These crewing conditions and the cap of credit hours or flying hours make the roster problem mathematically challenging. The common CR formulation takes the following form:

$$\min C = \sum_{j \in R} c_j x_j$$

(5)

where c_j is the cost of choosing roster x_j, among all possible roster candidates in set $R (\forall j \in R)$. The only set of constraints for this CR model is pairing coverage. In other words, each pairing must be covered by enough crew rosters on each operational day with the right skill mix. The objective of CR optimisation can be the minimisation of crew employment (i.e. the minimum crew or base size), the balance of working hours per roster period among crew, and the maximisation of crew productivity (in terms of flying or credit hours) … etc.

It should be noted that the total flying hours of a pilot is capped, so it is generally not a good idea to work a pilot too hard in roster periods early in the year and only have a small number of hours remaining from the cap later in the same year. If there are twelve roster periods in a year, after taking off six-weeks of annual leave, there are only 10.5 roster periods remaining for a pilot. If the total hour cap is 800 hours per annum, then on average, a pilot flies less than 80 hours per roster period. If we discount this figure by considering other non-flying duties and anticipated sick leave,

then at best a pilot can fly about 70-75 hours per roster period. If the average length of a one-day pairing is seven flying hours, then on average a pilot will work about 10 days per roster period; the industry norm is about 10-15 working days for a pilot for each roster period. Similar calculations can be made for cabin crew productivity.

Keyword: Roster period – is the period of time that a crew roster spans. This is usually four weeks for most western airlines. Crewmembers are also paid according to roster periods.

Results of CR are rosters for individual crewmembers factoring in many 'customisations' requested by crew such as annual leave, special requests … etc. Ultimately, all individual rosters must cover each flight and each aircraft operation in the timetable with the right skill mix. Finally, adequate numbers of reserve crewmembers are also required at each crew base to respond to operational uncertainties such as crewmember illness, flight delays, and other crewing disruptions.

11.5 Operational uncertainties and disruption management

The world is uncertain. This uncertainty is observed in airline operations with the numerous flight delays and cancellations that occur every day. As an example, the average on-time performance in the United States for 2014 was 76.25% (BTS, 2015). This particular result for on-time performance is typical throughout the world, suggesting that schedule perturbations resulting from uncertainties are unavoidable. *Disruption management* is a decision-making process employed by airlines to address these unavoidable uncertainties, aiming to reduce the impact of such perturbations and minimise any cost increases due to perturbations.

Keywords: Schedule Perturbation – a change to the scheduled departure or arrival times of flights during the day of operations. Possible causes include bad weather, late arriving passengers, or unplanned maintenance.

Keywords: Disruption Management – the process and actions taken by an airline, proactively or reactively, to minimise the increase in operational costs resulting from schedule perturbations.

The previous sections describe the airline planning process that is routinely undertaken to efficiently allocate the available resources, such as crew and aircraft. Schedule planning is typically conducted under the expectation that the day of operations will be performed without any schedule perturbations; however unlikely this may be. For example, an aircraft routing may be designed with very short turnaround times between each pair of flights. While this is an efficient use of an expensive resource (the aircraft), a delay on one flight in the routing is likely to cause further delays on all subsequent flights. This results in higher than expected operational costs and the delay propagation phenomenon that is commonly observed in airline networks (Wu, 2010).

Keyword: Delay Propagation – refers to the phenomenon that delays propagate through flights via passenger connections or resource connections between flights, e.g. aircraft and crew connections.

Since planning solutions designed with a focus on efficiency are susceptible to significant cost impacts from schedule perturbations, operations controllers are employed to ensure that daily operations are executed close to plan. The process undertaken by operations controllers to achieve this goal in the presence of schedule perturbations is called schedule recovery, which is a *reactive* form of disruption management. It is possible, however, to consider schedule perturbations during the airline planning process to reduce their prevalence or impacts on the day of operations. This involves using techniques that are termed 'robust planning'. Such methods are described as a *proactive* form of disruption management.

Keywords: Schedule Recovery – the actions undertaken by an airline on the day of operations to return operations back to plan following schedule perturbations; a reactive form of disruption management.

The practice of proactive disruption management

The main objective of proactive disruption management is to avoid or reduce the potential impacts of schedule perturbations on the day of operations. There have been many approaches proposed to achieve this goal, including:

- Increasing the minimum aircraft turnaround times (Eggenberg, 2009);
- Minimising propagated delay (Borndorfer et al., 2010, Weide et al., 2010, Dunbar et al., 2012); and
- Introducing swapping opportunities (Ageeva, 2000).

The first approach is very conservative and does not take into account any flight or time-of-day specific aspects. The application of this robustness technique involves planning for all aircraft to remain on the ground for longer time periods. For example, an aircraft routing with flights: FLT025 (SYD-BNE) – FLT026 (BNE-SYD) – FLT085 (SYD-CNS) may be formed such that a minimum turnaround time of one hour is schedule in between each pair of flights. Assuming that the aircraft requires a turnaround time of 40 minutes, this allows for a maximum delay of 20 minutes on each flight without causing departure delays, i.e. a 20-minute buffer.

If historical records show that departure of FLT025 (SYD-BNE) is regularly delayed by 30 minutes and FLT026 (BNE-SYD) is never delayed, then such a uniform turnaround time does not adequately match the expected delays. Setting the minimum turnaround time to 90 minutes for all flights will avoid delays for FLT025, but it is overly conservative for other connections, such as those following FLT026. Hence, it is particularly important to intelligently apply robust approaches to reduce the additional costs resulting from such techniques; see Wu (2006) for an example of flight time adjustments.

The second approach presented above is an example of a more intelligent, robust planning method. The robust tail assignment problem developed by Bordorfer *et al*

(2010) increases the ground time for aircraft, but only between flights where there is an expectation of delay propagating onto subsequent flights. This expectation is computed by reviewing historical delay data to calculate the probability of delay propagation for every possible pair of connected flights. Assuming the routing above is selected, the expected 30 minute delay for flight FLT025 (SYD-BNE) will impact the on-time performance of flight FLT026 (BNE-SYD). Hence, it is better to construct a routing where a turnaround time of at least 70 minutes is scheduled after the arrival of FLT025 (SYD-BNE). Note that with this turnaround time, it is not possible for the same aircraft to operated both FLT025 (SYD-BNE) and FLT026 (BNE-SYD). By taking into account historical delay data, turnaround buffer times can be more efficiently and effectively allocated to improve the utilisation of the fleet and contain the level of delays to a desired standard.

The final robustness technique given in the above list is an example of considering *reactive* disruption management approaches in a *proactive* setting. Aircraft swapping opportunities are periods of time when at least two aircraft of the same fleet type are planned to be on the ground at the same airport. If these opportunities exist, when one of the aircraft is delayed it is possible to use another to perform the flights that are originally schedule for the delayed aircraft. Aircraft swapping is a valuable tactical tool available to operations controllers to minimise the impact of schedule perturbations in disruption management. Increasing the prevalence of swapping opportunities at the scheduling stage aids the recovery process in operations, leading to less delays and lower operating costs.

CASE STUDY: Aircraft swapping robustness and recovery approach

The inclusion of aircraft swapping opportunities is one of the few robust planning approaches that are already widely employed by airlines. A major reason is that increasing the number of swapping opportunities in aircraft routing comes at very little additional cost to an airline.

The existence of swapping opportunities provides operations controllers with a tool to minimise the impact of flight delays, in particular delay propagation in a network. For example, a swapping opportunity exists for aircraft TA011, arriving in SYD at 1200

(operating flight FLT057) and departing at 1415 (flight FLT070), and aircraft TA027, arriving in SYD at 1230 (flight FLT059) and departing at 1445 (flight FLT072). A severe delay of two hours on flight FLT057 will prohibit aircraft TA011 from operating FLT070 on time, potentially propagating delays onto downstream flights. However, because this swapping opportunity exists, TA027 can be swapped to operate FLT070 and continue the routing assigned to TA011. TA011 is then used to operate FLT072 and the routing originally assigned to TA027. An advantage of this swap is that while aircraft TA011 is delayed, this delay does not propagate onto any other flights.

Increasing aircraft swapping opportunities in the planning stage is an approach used to improve the recoverability of the planned schedule. By increasing swapping opportunities, a greater number of options are available for the operations controllers in the event of a schedule perturbation. While this is a very specific technique aimed at improving the recoverability of the planned solution, more general approaches have been developed.

An example of improved recoverability for the tail assignment problem is given by Froyland *et al*. (2014) that involves simulating recovery scenarios to determine the additional operational costs associated with a given tail assignment solution. It is shown in Froyland *et al*. (2014) that the susceptibility of the tail assignment to disruptions can be reduced by using the information provided by the simulated recovery solution. In this case, recoverability is improved by incorporating this information about the potential actions that are performed by operations controllers in the event of a disruption during the construction and planning stage of the tail assignment problem.

The practice of reactive disruption management

Reactive disruption management is employed when a disruptive event causes a schedule perturbation and prohibits the original aircraft routings, crew pairings, and even passenger itineraries from being operated as planned. There are many different techniques available to the operations control centre to *recover* from a schedule perturbation. Such techniques include (Wu 2010: pp165-173):

- Delaying or cancelling flights;

- Rerouting of aircraft to operate a different sequence of flights than previously planned (same for crew);

- Using additional (reserve) crew to operate flights to avoid regular crew exceeding work limits; and

- Transporting crew as passengers (deadheading crew) to reposition them to operate flights out of different airports.

The employment of these recovery techniques by the operations control centre depends on the nature of the schedule perturbation. Since there are many inter-connected resources in an airline's operations, there are conflicting objectives during the recovery process. Primarily these recovery techniques are employed to minimise the additional costs to the airline, which include additional crew costs and lost revenues. However, actions such as delaying and cancelling flights have a significant impact on passenger itineraries and service satisfaction, so these actions must be carefully evaluated in the recovery process. Weighing up the direct and indirect costs of recovery actions such as those related to reserve crew and passenger satisfaction is a critical consideration during disruption management.

CASE STUDY: Automated Decision Support Systems

The expansion of airline networks and services in the United States throughout the 1980s and 1990s prompted an interest in automated decision support systems. During much of this period, irregular operations were handled within airline operations control centres by practitioners basing recovery decisions primarily on their vast experience and intuition. To address the rising prevalence of irregular operations, major airlines in the United States invested heavily in automated systems. Initially these systems collected and displayed operational information and data. This complemented the work performed by the operations controllers by providing up-to-date information about the airline's operations.

The benefits of providing this information was quickly realised, with Rakshit et al. (1996) reporting significant reductions in delay minutes and the number of delayed flights. Over time, with the development of optimisation approaches aimed at solving airline problems for irregular operations, decision support systems were designed to provide controllers with suggestions of flight delays, cancellations, and possible new aircraft routings and crew pairings. Through advances in optimisation techniques, the state-of-the-art in decision support systems is progressing towards fully automated airline recovery systems.

There have been many attempts to develop optimisation approaches to solve airline recovery problems. A good review of optimisation techniques applied to this problem is presented by Clausen *et al* (2010). Given the complexity of the complete airline recovery problem, similar to the planning process in practice and in research, it is common to focus on each key resource in isolation. Specifically, the airline recovery process involves: 1) constructing an updated schedule, 2) rerouting aircraft to operate this schedule, 3) allocating crew to the rerouted aircraft schedule, and 4) construct new itineraries to ensure disrupted passengers arrive at their final destinations.

To improve the result from solving this set of sequential problems, it is ideal for two or more of these stages to be integrated in a single model. For example, the scheduling decisions of delaying and cancelling flights greatly affect the aircraft and crew recovery solutions. Hence, it is useful to include these decisions in either the aircraft or crew recovery problems, or in both. Similarly, the interaction between the aircraft and crew can be better modelled by focusing on both resources simultaneously.

A current focus for research is the development of a fully integrated airline recovery problem. Until recently, there have been very few attempts to develop an efficient implementation of this problem, due to its overall complexity. Similar to the case for the planning stage, the integration of all stages of the recovery process will reduce operational costs by more efficiently deploying the available resources of crew and aircraft. A recovery problem integrating crew and aircraft is presented by Maher (2015) as a possible feature to be included in automated recovery systems. Also, Petersen *et al*. (2012) demonstrates the potential of a fully integrated approach

including schedule, crew, aircraft, and passengers. In both cases, the practical implementation into a decision support system is still not clear. Schedule perturbations affect every aspect of an airline, requiring every detail, however small, to be considered in an airline recovery solution.

Mathematical formulation of the airline recovery problem

The mathematical formulation of airline recovery problems is very similar to the equivalent planning problems. Following on the previous formulation example given for the aircraft routing problem, this section presents a mathematical model for the rerouting of aircraft, commonly called the 'aircraft recovery problem'. As stated previously, the complete airline recovery process involves a number of stages, some of which are amenable to integration. In addition to the rerouting of aircraft, the model presented in this section also includes schedule recovery decisions for flight delays and cancellations.

The aircraft recovery problem is solved for a single fleet type and aims to assign exactly one aircraft to each flight after a schedule perturbation. As a result of schedule perturbations, it is not always feasible for every flight to be assigned an aircraft; in these situations the flight must be cancelled. Additionally, the modification of flight departure times, in the form of flight delays, is permitted. The notation used in the previous aircraft routing problem is adopted here with some modifications to specifically describe the aircraft recovery problem.

Each flight j that an aircraft from fleet f must be assigned to is contained in the set N_D^f; the subscript D indicates that the contained flights all depart after the schedule perturbation but before a specified end-of-recovery time. Each aircraft is individually recognised by its tail number on the day of operations and assigned a specific routing, i.e. the Tail Assignment. Each routing p that aircraft r can be assigned to is contained in the set P^r. Finally, the binary variables z_j are included, which equal 1 if flight j is cancelled and 0 otherwise. The aircraft recovery problem is given by the following:

$$\min \sum_{r \in R} \sum_{p \in P^r} c_p y_p + \sum_{j \in N_D^f} d_j z_j$$

(6)

$$\text{subject to } \sum_{r \in R} \sum_{p \in P^r} a_{jp} y_p + z_j = 1 \; \forall j \in N_D^j,$$

$$\sum_{p \in P^r} y_p \leq 1 \forall r \in R,$$

$$y_p \in \{0,1\} \forall p \in P,$$

$$z_j \in \{0,1\} \forall j \in N_D^j.$$

The objective of the aircraft recovery problem minimises the cost associated with recovery, namely flight delay and cancellation costs. Different from the aircraft routing problem, the cost coefficients c_p generally have non-zero values to reflect the varying costs of flight delays and their impacts on passengers. Similarly, the coefficients d_j have non-zero values that aim to quantify the impact of flight cancellation on passengers. The first constraint ensures that each flight departing after the schedule perturbation is assigned to an aircraft from fleet f or is cancelled. The second set of constraints is additional for the aircraft recovery problem, which restricts the number of routings assigned to each aircraft to at most 1, so each aircraft does not have to be assigned a routing in the recovered solution. The final two constraints restrict the routing and flight cancellation variable values to 0 or 1.

The primary difference between the aircraft routing problem and the aircraft recovery problem is the additional variables that are used to indicate flight cancellations. Another major difference, which is not obvious from the above formulation, is that the routings p may include flights with a departure time that differs from the original schedule, i.e. flight delays. This indicates that flight delays are considered during the re-routing phase, which is either done heuristically or dynamically using a column generation technique (Barnhart et al., 1998; Desaulniers et al., 2005). This further emphasises the difficulties previously discussed in the aircraft routing section, relating to the complete enumeration of all routings because theoretically, there are infinitely many potential departure times for each flight.

11.6 Future airline scheduling – the integrated approach

Airline scheduling has been conducted in the industry by a 'sequential optimisation' approach following the sequential task order: schedule generation, fleet assignment, aircraft routing, and crew rostering. There are two main drivers that push airlines to adopt such a sequential approach in scheduling. First, airlines are required to publish schedules well ahead of operations, often one season (six months) in advance. This requirement pushes airlines to conduct schedule generation and fleet assignment early.

Second, the mathematical problem and the complexity of airline scheduling involving the four tasks is so huge and challenging that airlines simply could not build a single model that solves the whole scheduling problem. Consequently, the mathematical problem of airline scheduling has been approached by the 'divide-and-conquer' concept by breaking down the scheduling problem into four main tasks. This approach also fits the timeline of airline scheduling well by allowing airlines to first solve the problems of timetabling and fleet assignment. Then, airlines can solve the problems of aircraft routing and crewing closer to the day of operations; commonly about 2-3 months ahead of operations.

Although this 'divide-and-conquer' concept has been prevalent in the industry and academic literature for decades since the early 1980s, the most significant drawback of this approach is the 'quality' of solutions for each task and the airline scheduling problem as a whole. Since the output of a task is used as the input for a subsequent task in scheduling, the solution for the subsequent task is limited by its inputs, i.e. the outputs of the previous task. This causes the solution quality to deteriorate along the stages of scheduling; poor fleet assignments result in sub-optimal aircraft routings, and this in turn causes higher costs in crew pairing and rostering.

With the advance of mathematical science and computing power, it is now feasible to solve the whole airline scheduling problem using an 'integrated' approach, i.e. integrating two or more scheduling tasks into one single formulation. The integration of scheduling tasks improves the solution quality by eliminating constraints that are

imposed by individual scheduling tasks. Lohatepanont and Barnhart (2004) propose an integrated model for schedule generation (timetabling) and fleet assignment. By allowing flight times to change in the solution process, this integrated model addresses the fleet assignment problem and produces better quality results for both schedule generation and fleet assignments.

Rosenberger *et al.* (2004) and Haouari *et al.* (2009) propose integrated optimisation models by combining the fleet assignment model and the aircraft routing model. When performed separately and sequentially, the results of the fleet assignment model often yield infeasible or inferior solutions for the aircraft routing model due to: 1) maintenance and specific aircraft routing constraints imposed by airlines, and 2) the limits imposed by fleet assignment results. With the integrated model, Rosenberger *et al.* (2004) and Haouari *et al.* (2009) report that the solution quality of both fleet assignment and aircraft routing is significantly improved, producing better solutions than the traditional sequential approach.

Crew roster optimisation is based on results of crew pairing, which is based on results of aircraft routing. Hence, there has been significant interest in integrating crew pairing and aircraft routing, hoping that crew rostering results can be improved further with lower pairing costs. Cohn and Barnhart (2003) extend the concept presented by Cordeau *et al.* (2001) and build an integrated aircraft routing and pairing model by incorporating key maintenance routing decisions.

Weide *et al.* (2010) use an iterative approach to solve routing and pairing problems sequentially by using feedback loops. By 'relaxing' routing solutions while solving the pairing problem, Weide *et al.*(2010) are able to improve crew pairing solutions without violating routing conditions. Dunbar *et al* (2012; 2014) further extend Weide's framework by incorporating delay propagation in an integrated routing and pairing problem setting. By allowing flights to be re-timed in a small time window when solving the routing problem, Dunbar *et al.* (2012; 2014) show that solution quality can be significantly improved for both routing and pairing problems; some improvements are in the order of 10 to 30 per cent.

The studies by Sandhu and Klabjan (2007), and Papadakos (2009) are perhaps the pioneers in integrating three tasks of airline scheduling in a single model: fleet assignment, aircraft routing, and crew pairing. While mathematically more challenging than before, the improvement in solution quality by integrating three stages of airline scheduling is impressive in the order of tens of million dollars for a typical European airline per year.

The future of airline scheduling is heading towards integrated modelling and robust scheduling, as we have previously discussed in the section of disruption management. Interested readers are encouraged to seek relevant literature on this line of work and explore future trends in airline scheduling.

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