An integrated decision support tool for airlines schedule recovery during irregular operations

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Received 28 June 2004; accepted 15 December 2006
Available online 30 January 2007

Abstract

This paper presents a decision support tool for airlines schedule recovery during irregular operations. The tool provides airlines control centers with the capability to develop a proactive schedule recovery plan that integrates all flight resources. A rolling horizon modeling framework, which integrates a schedule simulation model and a resource assignment optimization model, is adopted for this tool. The schedule simulation model projects the list of disrupted flights in the system as a function of the severity of anticipated disruptions. The optimization model examines possible resource swapping and flight re-quoting to generate an efficient schedule recovery plan that minimizes flight delays and cancellations. A detailed example that illustrates the application of the tool to recover the schedule of a major US air-carrier during a hypothetical ground delay program scenario is presented. The results of several experiments that illustrates overall model performance in terms of solution quality and computation experience are also given.

Published by Elsevier B.V.

Keywords: Irregular operations management; Airlines scheduling; Ground delay programs; Simulation and optimization

1. Background

On-time performance of airlines schedule is key factor in maintaining satisfaction of current customers and attracting new ones. However, airlines planned schedules are often subjected to numerous sources of irregularity. In particular, weather accounts for the most part of recorded flight delays (Ageeva, 2000). When adverse weather conditions are anticipated at one airport, the aviation authority (e.g., the Federal Aviation Administration (FAA) in the US) issues a Ground Delay Program (GDP) at this airport. The purpose of this GDP is to increase the time gap between successive flight landings in order to ensure safe operations during the adverse weather period. Under most GDPs, the available number of slots for flight landings becomes less than what is required for the original planned schedule...
(Ball et al., 2000; Abdelghany et al., 2004c). Therefore, a scheduled flight could be held at its origin, diverted to a nearby airport, or in the worst case it could be canceled. These disruptions in the planned schedule impact availability of crews and aircrafts for future flights. For instance, when a flight is delayed, its crewmembers may misconnect their next scheduled flights. They may also exceed the limits for legal duty periods; resulting in not completing remaining flights in their planned schedules. Hence, one flight delay could have a cascading downline disrupting impact over time and space unless appropriate recovery actions are taken.

For a small airlines network, tracking and efficiently recovering the downline impact of few delayed flights could be a simple task. However, for major airlines with more than 2000 daily flights, if GDP programs are issued at one or more airports, tracking and recovering the downline impact of these GDPs could be extremely challenging and time consuming (Monroe and Chu, 1995). Consequently, considerable attention has been given to develop decision support tools to limit flight delays associated with GDPs for major commercial airlines. A recent comprehensive review of concepts and models used to develop these tools can be found in Clausen et al. (submitted for publication). For instance, Teodorovic and Guberinic (1984), Teodorovic and Stojkovic (1990), Jarrah et al. (1993), Talluri (1996), Yan and Yang (1996), Yan and Young (1996), Cao and Kanfani (1997a,b), Argüello and Bard (1997a,b), Thengvall et al. (2000, 2003) and Rosenberger et al. (2003) describe different recovery models with the decision variables are describing aircraft rerouting plans in order to improve overall system performance during irregular operations. Similarly, Clarke (1997), Wei et al. (1997), Lettovsky et al. (1998), Stojkovic and Soumis (1998), and Abdelghany et al. (2004a) describe crew-oriented recovery models. One drawback of these models is that they consider only one resource type. In other words, they ignore evaluating the impact of recovery actions generated for one resource on other unconsidered resources. For example, when a decision is made to delay a flight because of the unavailability of its aircraft, investigating the impact of this delay on crew duty period is ignored. Up to the authors’ knowledge, the problem of developing an integrated decision support tool that simultaneously recovers multiple resources is not thoroughly considered in the literature.

This paper presents an integrated Decision Support Tool for Airlines schedule Recovery during irregular operations, DSTAR. The tool allows operators in the airlines control center to detect current and future flight delays and to generate proactive integrated recovery plan to avoid these delays. DSTAR implements a greedy optimization approach in a rolling horizon framework. The framework integrates a schedule simulation model and a resource assignment optimization model. The schedule simulation model predicts the list of disrupted flights in the system as function of resources availability and applied legality rules. The optimization model seeks to find the optimal plan of crew and aircraft swapping, reserve utilization and flight re-quoting to recover the projected list of disrupted flights. The main contributions of this tool are as follows. First, it integrates recovery decisions for multiple heterogeneous airline resources (aircraft, pilots, and flight attendants) with different scheduling constraints. Second, the tool provides proactive recovery plans for schedule disruption management, so it recovers flights with anticipated resource problems prior to its departure time. Finally, the tool enables near real-time response. As presented hereafter, efficient recovery plans for severe schedule disruptions are generated in less than 1 minute.

The paper is organized as follows. A description of resource possible operation violations during irregular operation conditions is presented in Section 2. Section 3 illustrates interdependency among airline resources and the concept of slack time. Current practice in airlines operation management and schedule recovery is described in Section 4. Section 5 formally describes the airlines recovery problem. The overall framework of DSTAR is presented in Section 6, which also describes the mathematical formulation of the integrated recovery problem. A detailed illustrative example is presented in Section 7. The application of DSTAR on the schedule of a major US airline is presented in Section 8. The model computation experience and solution quality are presented in Section 9. Finally, conclusions are presented in Section 10.

2. Resource violations during irregular operations

Crew schedules are typically designed in what is known as trippairs. A trippair is a workload assignment for each pilot and flight attendant. The length
of a trippair is usually in the range of one to five days where each day represents one duty period. A trippair originates from one base station and ends at the same base station (domicile). A trippair that belongs to one domicile is assigned to crews who are based at this domicile. Between two successive duty periods, crewmembers are given a rest period known as layover. The lengths of duties and rest periods are determined based on a set of rules that are specified in the FAA regulations and crew agreements. These rules guarantee safe operation and good quality-of-life for the crew. Between two successive segments in the same duty period, crewmembers are given a reasonable connection time that is enough to connect from the arrival gate to the next departure gate, if they are different. Fig. 1a shows a typical 2-day trippair that starts and ends at domicile “A” and has away-from-home layover at station “H”. In case of irregular operation conditions, different crew operation violations could occur, which include:

2.1. Misconnect violation

It occurs when a connecting crewmember is projected to arrive late such that she/he is unable to connect on time to the next flight in the same duty period. Fig. 1b shows an example of a typical misconnect violation. When flight B-S is delayed, the crewmember’s ready time is shifted beyond the scheduled departure time of the next flight. Therefore, flight S-H cannot depart on time unless the late crewmember is substituted at station S.

2.2. Rest violation

This violation is similar to the misconnect one. It occurs when a crewmember gets a rest period

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**Fig. 1a.** A typical trippair in normal operation conditions.

**Fig. 1b.** Example of misconnect violation.
that is less than the legal layover because of late arrival at the end of the preceding duty period. In this case, the crewmember would be unable to fly the first flight segment in the next duty period on time. Fig. 1c shows an example of a typical rest break. When flight S-H is delayed, the layover becomes less than the legal layover. The first flight of the next duty period (flight H-L) cannot depart on time since the crewmember must get her/his legal rest before starting the next duty period.

2.3. Duty limit violation

It occurs when the actual duty period exceeds the duty period limit due to delay of one or more flights in the duty period. In this case, the remaining flights in the duty period cannot be flown using their original crewmember. Fig. 1d shows an example of a typical duty break. Flight S-H is delayed and its new arrival time passes the duty limit for the crewmember. Therefore, a substitute crewmember should be found at station S to fly flight S-H as its originally assigned crewmember cannot work beyond her/his duty period limit.

2.4. Open position

It occurs in case of no show of a crewmember or when the up-line flight is canceled such that the crewmember is not available to fly her/his next assignment. No show of a crewmember could be due to illness or any other emergency.

Similar to crew, aircraft routes are designed to cover a set of consecutive flights (route). The time interval between two successive flights is scheduled for the aircraft service/maintenance. Aircraft service
includes fueling, cleaning, baggage handling and catering. At some designated stations, maintenance activities are performed for the aircraft. Aircraft maintenance items are usually done on cyclic basis, which could be scheduled based on dates, number of flown hours, number of landings/take-offs, etc. Aircraft routes are designed to ensure that all maintenance activities are performed at the qualified stations and at the required times. Under irregular operation conditions, the same set of violations that are described for crew could also occur for the aircraft. For example, misconnect violation could take place if an aircraft arrives late and its projected ready time is beyond the scheduled departure time of the next flight.

3. Resources connectivity and slack time

The actual departure time of any flight is the latest of its scheduled departure time, the latest ready time among all its operating resources, and its issued GDP departure time (if any). An aircraft is ready only after it gets the necessary service or after its scheduled maintenance items are performed. Similarly, crewmembers are ready after they connect from the arrival gate to the next departure gate, or after they receive the legal rest period between two successive duties. Fig. 2 shows an example of a small flight network that consists of seven flights (numbered from F1–F7). Each flight is represented using a thick line where start and end of the line represent the departure and arrival times of the flight, respectively. Arrows represent connecting resources between flights. One arrow represents one resource (aircraft, pilot, or FA). The start of the arrow is the arrival time of the inbound flight. The end of the arrow is the resource ready time to operate the next flight. As shown in the Figure, flight F1 departs at D1 and arrives at A1. Upon arrival of flight F1, resource R_{F1F3} connects to flight F3 and resource R_{F1F4} connects to flight F4, respectively.

In the normal operation conditions, all resources are planned to be ready before the scheduled departure time of their next assigned flights by some slack time (\( S \geq 0 \)). A resource slack time is the difference between the resource’s next flight departure time and its ready time. As shown in Fig. 2, resources R_{F1F3} and R_{F1F4} have positive slack times of \( S_{F1F3} \) and \( S_{F1F4} \), respectively. If a resource is delayed within its slack, its next downline flight could still depart on time. If \( S_{F1F3} \) is less than \( S_{F1F4} \), flight F1 could be delayed \( S_{F1F3} \) minutes without affecting any downline flights. This defines the flight’s downline slack, which is the longest time interval a flight can be delayed without affecting any downline flights. Computationally, a flight downline slack is the least slack among all its outbound resources. Now assume that flight F1 is delayed such that it departs at D1’ as shown in Fig. 3. If the delay (D1’ – D1) is greater than the downline slack of flight F1, one or more of the downline flights that use resources out of flight F1 would be affected. As shown in Fig. 3, the delay (D1’ – D1) is greater than the slack time of the connecting resources causing these resources to disconnect flights F3 and F4. Thus, if no recovery actions were considered, flights F3 and F4 would be delayed based on the arrival time of their resources from flight F1.

For flight F4, assume that the inbound resource R_{F1F4} is an aircraft while the inbound resource R_{F2F4} is a flight attendant. Also, assume that there

![Fig. 2. Resources connectivity during normal operation conditions.](image-url)
is no substitute is available for this aircraft $R_{F1F4}$, and that any delay to flight $F4$ would cause a duty limit violation for flight attendant $R_{F2F4}$. As there is no substitute for the aircraft $R_{F1F4}$, flight $F4$ would be delayed until its aircraft becomes ready, causing a duty limit violation of the flight attendant $R_{F2F4}$ as shown in Fig. 3. Therefore, this flight attendant cannot serve on flight $F4$. Additionally, delaying flight $F4$ causes its outbound resources to misconnect their next flights. Resources $R_{F4F6}$ and $R_{F4F7}$ would misconnect flights $F6$ and $F7$, respectively. This example demonstrates the intensive connectivity among resources and the importance of integrating these resources while recovering a state of irregular operations.

4. Current practice

A typical operation control center (OCC) in major commercial airlines consists of four main desks, which are aircraft routers, pilot schedulers, Flight Attendant schedulers and controllers. The first three desks are responsible for handling resource violations that might occur during irregular operations. Controllers coordinate recovery acts of these three desks and take the final decision for each flight. In case of any schedule disruption due to GDP, or any other reason, information on affected flights is sent to the OCC desks. This information is analyzed to evaluate the impact of this disruption on other downline flights. If a resource violation is anticipated, the OCC desks work on fixing this violation using one or a combination of the following recovery actions:

4.1. Calling standby/reserve resource

Airlines always maintain airport standby and home reserve resources at the main stations (hubs) to recover unexpected system breaks under irregular operation conditions. In case of a resource violation, the violating resource is substituted by one of the available standby/reserve resources. The standby/reserve resource could be at the same station where the violation occurs or deadhead (a crew-member travels as a passenger) from another station. The newly assigned resource must have same qualifications as the original resource and does not violate any of the mandatory operation rules.

4.2. Swapping resources

Swapping is to trade resources that have later assignments with resources that have earlier broken assignments. Swapped resources could be at the same station where the violation occurs or deadhead from another station. A swap could be two-way or multi-way. In the two-way swap, two tasks are exchanged between two resources. In the multi-way swap, the exchange of assignments goes in a cycle between more than two resources. The condition is that the swapped resources would be ready before or shortly after (in case of delay) the scheduled departure time of the new assignment.

4.3. Re-quoting (delaying)

In this case, new departure/arrival times are quoted for the flight based on the ready times of
its delayed resources, or ready times of newly assigned resources. As such, re-quoting could be a recovery action by itself or joined with resource swapping or standby/reserve calling. All crewmembers on the re-quoted flight have to be checked to make sure that no duty violation is occurring because of this delay.

4.4. Cancellation

If no recovery is found for a violating resource within a reasonable time window, the only available decision is to cancel this flight and rebook its passengers on next flights or even on other airlines. Due to the high cost of flight cancellation, all possible recovery scenarios have to be thoroughly investigated before considering a cancellation decision.

In practice, the recovery process is usually done on a flight-by-flight basis rather than developing one integrated efficient plan for all flights in the system. Furthermore, the recovery process is usually performed sequentially by resource type. The recovery process always starts by recovering the aircraft, then pilots, and finally FAs. Decisions on what actions to be taken could be conflicting among the different management groups. For instance, aircraft routers could quote a new departure time for a flight to recover a late turn of the aircraft. However, pilots who are assigned to the same flight could violate their duty period limit due to such delay. Thus, an action to recover the aircraft causes a pilot break. In general, a recovery plan could take several iterations among the different groups until it is finalized, which represents a time-consuming process in a time-critical environment. In addition, the recovery process is usually not fully automated. Therefore, system operators could have limited capability to anticipate all system breaks and explore all possible solutions for their recovery. Consequently, the quality of a recovery plan usually depends on the level of experience of system operators who are handling projected system disruptions. Such situation usually results in an unacceptable fluctuation in overall system performance.

5. Problem definition

Define:

- \( f \) flight index
- \( k \) an index for resource type (aircraft, pilot, FA)
- \( g_{kf} \) total number of resources of type \( k \) required for flight \( f \)
- \( r_k \) an index for resources of type \( k \) in the system, \( r_k \in R_k \)
- \( p_{rf} \) the part of the crew trippair or aircraft route (starting with flight \( f \)) that can be covered by resource \( r \)
- \( b_{rf} \) a binary variable to indicate if resource \( r \) is available to cover any part of a broken trippair or aircraft route, 1, if \( p_{rf} > 0 \), 0, otherwise
- \( a_{rf} \) the ready time of resource \( r \) to operate flight \( f \)
- \( x_{rf} \) a binary variable to indicate if resource \( r \) is assigned to flight \( f \), 1, if assigned, 0, otherwise
- \( c_{cf} \) the cost of assigning resource \( r \) to flight \( f \)
- \( cd_f \) the cost of 1-minute delay of flight \( f \)
- \( cc_f \) the cost of canceling flight \( f \)
- \( v_r \) the duty (usage) limit of resource \( r \)
- \( t_f \) the scheduled departure time of flight \( f \)
- \( m_f \) actual departure time of flight \( f \)
- \( n_f \) actual arrival time of flight \( f \) with upper bound value \( UB(n_f) \)
- \( T_f \) expected trip (block-to-block) time of flight \( f \)
- \( L_f \) a binary variable to indicate flight cancellation status, 1, if flight \( f \) is cancelled, 0, otherwise
- \( q_{kk'} \) an indicator to represent resources qualification and compatibility, 1, if resource types \( k \) and \( k' \) are compatible to operate the same flight, 0, otherwise.

Given is a recovery horizon of interest \( h \), which includes \( F \) flights. Each flight is defined using its number, origin, destination, and scheduled departure/arrival times. The originally assigned resources to all flights in the horizon \( h \) are also given. Each resource in the system is defined by a unique identification index \( r_k \in R_k \). Given also is the list of flights affected by the issued GDP, or any other disruption reason. The objective is to determine the downline impact of these disruptions, which includes potential resource violations and associated disrupted
flights in the horizon \( h \). A resource is marked as violating, if it cannot complete its originally scheduled route/trippair as described earlier in Section 2. A flight that uses one or more violating resources is marked as disrupted flight. The objective also is to develop an efficient recovery plan to fix all disrupted flights such that it minimizes total system cost resulting from resource reassignments, flight delays and flight cancellations. This recovery plan is developed in terms of new aircraft routes and crew trippairs that cover the list of disrupted flights in the horizon \( h \).

Available resources that can be used in the recovery process include (1) standby/reserve resources, if any, (2) resources of cancelled flights, (3) violating resources that cannot complete their original assignment but could be reassigned to new tasks, and (4) good resources that could be swapped to cover other violating resources. Two main operational constraints control the use of these resources in the recovery plan. First, resources assigned to operate a flight must be qualified for this flight and compatible with other resources assigned to the same flight. For example, if an aircraft of certain fleet is assigned to a flight, pilots who are assigned to the same flight must be qualified to fly this fleet type. The resource qualification matrix \( q \), which defines resource compatibility, is assumed known. If two resources of type \( k \) and \( k'' \) are compatible to operate the same flight, the parameter \( q_{kk''} \) is equal to one, and zero otherwise. Second, used resources should comply with all mandatory operation rules set by the FAA and the crew agreements. For example, if a flight is delayed, this delay should cause no violation to the aircraft’s scheduled maintenance activities or to the crew duty limits.

6. Methodology

6.1. Overall system framework

As shown in Figs. 4 and 5, the modeling framework integrates a schedule simulation model and an optimization solver in a rolling horizon framework. It starts by activating the schedule simulation model to simulate all flights and their resources in the horizon \( h \). If the system is subjected to GDPs or any other sources of irregularity at one or more stations, which result in delaying/canceling some flights, information on these delayed/canceled flights is made available to the simulation model. The model projects all potential downline resource violations in the horizon \( h \) due to the introduced delays/cancellations. As described earlier in Section 2, resources violations may include misconnect, rest and duty limit violations. If a resource violation is projected, all remaining flights in the route/trippair of this resource are considered as disrupted flights.

Abdelghany et al. (2004b) describes in details the schedule simulation model used in DSTAR. In this model, the airline’s daily schedule is represented in the form of a directed acyclic graph with its nodes are the different scheduled events, and its arcs are the scheduled activities between these events. The cost associated with an arc is the expected time duration of the activity represented by this arc. As shown in Fig. 6, scheduled events include flight departures, flight arrivals, crew duty starts, crew releases from duty, aircraft maintenance starts and ends etc. The in-between activities include aircraft taxi-out and taxi-in, flying, crew connections and layovers, etc. Slack times are represented using dummy arcs with no cost. Using this graph representation, the model applies the classical label-correcting longest path algorithm to determine the earliest possible time at which the different events could occur while considering all operation constraints that govern the FAA and crew legality rules. If a label of one node is changed from what is originally quoted, it implies that a delay is projected to the event presented by this node. If this event represents a flight’s departure time, this flight is marked as disrupted flight. Also, the resource causing this delay is marked as violating resource.

Once the list of disrupted flights is projected, the first set of resource-independent flights within the horizon \( h \) is determined. Resource-independent flights are defined as flights that are operationally infeasible to feed resources to each other. In other words, these flights are temporally and/or spatially constrained such that they cannot exchange resources. For example, if two flights were scheduled to depart from two different stations at the same departure time, it would be operationally infeasible for these two flights to exchange resources. Also, by definition, two consecutive flights in the same duty/route are not resource-independent as the earlier flight feeds the crewmember/aircraft to its consecutive flights in this duty/route.

This earliest set of resource-independent flights represents the first recovery stage in the horizon. The start of this stage is the departure time of the earliest flight in the set, while the end of the stage is the arrival time of the latest flight in the set. In
addition to the disrupted flights in the set, some undisrupted flights (flights with no resource violations) could be included. These flights are included to check the possibility of swapping their resources with the resources of disrupted flights in the set. If an undisrupted flight is included, it is considered as one of the disrupted flights in the set. Undisrupted flights included in the set should satisfy the resource-independence condition described above.

The originally assigned resources to all flights in the current recovery stage are added to the bank of resources that is used in the recovery process. These resources include violating resources that cannot complete their original assignments and good resources that are still able to fly their assignments. The reason to include the non-violating resources of the disrupted flights as part of the resources bank is to be able to reassign these resources to other flights if their disrupted flights are cancelled.

As flights in the same set do not exchange resources, decisions on their recovery could be made simultaneously. For this purpose, the optimization solver is activated to recover all flights in the first stage. The input to the solver includes the list of disrupted flights in this stage and the bank of available resources. The optimization solver minimizes the total system cost resulting from resource reassignments, flight delays and flight cancellations. It efficiently assigns available resources to existing disrupted flights in the current stage. At the end of a stage and based on the recovery decisions made in this stage, resources information are updated. Crew information is updated by determining the crew new locations in the network, crew new duty limits, and required layover rests. Similarly, the new positions of all aircrafts together with their next due maintenance activities are updated.

Recovery actions decided in an earlier stage could add/remove more flights to the list of
disrupted flights. For example, as described in Section 3, a flight delay beyond the downline slack could create a break for other resources, which might lead to more downline disrupted flights. Accordingly, the list of disrupted flights in the remaining part of the horizon has to be updated based on the output of the optimization solver in the preceding stage. Subtracting the length of the preceding stages from the total horizon, the flight simulation model is again activated to project the new list of disrupted flights in the remaining part of the horizon $h$.

Based on the results of the simulation model, the next recovery stage is determined. This stage con-
sists of the next available set of resource-independent flights as described earlier. The optimization solver is again activated to recover this stage. The process continues until no more disrupted flights appear in the system or when the maximum recovery horizon is reached. Finally, the output of the optimization solver in every stage is retrieved. This output is used to generate new aircraft routes and crew trippair that covers the horizon of interest. Also, the list of all re-quoted and cancelled flights in the horizon \( h \) is generated.

6.2. Preprocessing

Three preprocessing steps are conducted at the beginning of each stage to determine the following:

- The set of resource-independent flights in the current stage.
- The set of undisrupted flights whose resources are candidates for swapping with the resources of the disrupted flights in the current stage.
- The cost associated with the assignment of a given resource to a flight, which is used by the optimization solver.

6.2.1. Resource-independent flights

Different strategies could be used to determine the set of resource-independent flights. In the current implementation, all flights that are simultaneously out-of-block are assumed to be resource independent flights. The following three-step heuristic is used to determine the set of resource-independent flights. First, all flights in the horizon are ordered chronologically based on their departure times. Second, the first flight to arrive among all disrupted flights that are not previously included in any earlier recovery stage is determined (the critical flight of the stage). This flight is included in the current stage. Third, all flights that not included in previous stages and depart before the arrival time of the flight found in step two are determined and included in this stage. As shown in Fig. 7, flight F2 is the critical flight. Flight F1 is the only flight that departs before the arrival of F2. Thus, flights F2 and F1 are grouped in stage 1. Similarly, flights F3, F4 and F5 are grouped in stage 2, and flights F6 and F7 are grouped in stage 3.

6.2.2. Use of resources from undisrupted flights

As mentioned earlier, the framework allows marking some undisrupted flights as disrupted flights in order to check the possibility of swapping their resources with the resources of the disrupted flights. It is generally expected that adding more undisrupted flights to the problem increases the possibility of finding more opportunities for efficient resource swapping. However, this adds to the run time required to generate the solution at each stage. Also, changing the schedule of undisrupted crew unnecessarily is not a preferred option, as it affects

Fig. 7. Sets of independent flights.
the quality-of-life measures of the crew. Different ad
hoc rules could be used to determine the set of
undisrupted flights to include at each stage. In the
current implementation, all flights that depart
within $X$ minutes from the same airport of each dis-
rupted flight and satisfy the resource-independence
condition described above is included in the stage
under consideration. The analysis presented hereaf-
ter examines the quality of the recovery plan with
different values for the parameter $X$.

6.2.3. Assignment cost

Assignment cost of a given resource to a flight is
modeled such that it meets different operation
conditions. These conditions include, for exam-
ple, minimizing deviation from the original
schedules (swapping), minimizing flight delays,
minimizing the use of standby and reserve
resources, reducing number of crew deadheads/air-
craft ferrying and minimizing the resources’ idle
time in the system. As such, the cost of assigning
a resource to flight is composed of the following
elements:

- Swapping cost: considers the case when the can-
didate resource is moved from its originally
planned route/trippair to cover a flight in another
route/trippair.
- Standby/reserve cost: considers the case when the
candidate resource is a standby or reserve.
- Deadhead cost: considers the case when the can-
didate resource is deadheaded from another sta-
tion to the origin of the disrupted flight.
- Idle time cost: A cost term is added for every
minute that the candidate resource would remain
idle if assigned to the disrupted flight.

The values of these cost parameters are user-spe-
specific. Users can evaluate the resulting solutions
through using different combinations of these cost
parameters. In addition, operation situation might
force the use of certain cost scenario. For example,
air-carriers usually limit the use of their reserve
resources in the beginning of the month to ensure
that enough reserve resources are available for the
entire month. Thus, an operation mode in which
Standby/reserve cost is set at high value is expected.
Similarly, if crewmembers were complaining of
significant changes in their planned schedules dur-
ing a previous season, operators might run the
model with high swapping cost to consider these
complains.

6.3. Mathematical formulation

The recovery problem at each stage is formulated
mathematically in the form of a Mixed Integer Pro-
gram (MIP) as given below:

**Objective function:**

Minimize

$$
\sum_{f \in F} \sum_{r} c_{rf} \cdot x_{rf} + \sum_{f \in F} \sum_{s} c_{df} \cdot [m_f - t_f] \\
+ \sum_{f \in F} c_{cf} \cdot L_f
$$

(1)

Subject to:

$$
x_{rf} \leq b_{rf} \quad \forall f \in F, r
$$

(2)

$$
\sum_{f \in F} x_{rf} \leq 1 \quad \forall r
$$

(3)

$$
[1 - L_f] \cdot g_{rf} = \sum_{s} x_{rf}
$$

(4)

$$
\forall f \in F, k
$$

(5)

$$
\forall f \in F, k, k', k \neq k'
$$

(6)

$$
m_f \geq a_{rf} \cdot x_{rf} \quad \forall f \in F, r
$$

(7)

$$
L_f \leq t_f \quad \forall f \in F
$$

(8)

$$
m_f \geq t_f \quad \forall f \in F
$$

(9)

$$
x_{rf} \in \{0, 1\}, L_f = \{0, 1\},
$$

(10)

and $m_f, n_f$ are integers

The formulation is an extension of the crew
recovery formulation given in Abdelghany et al.
(2004a) to include more than one resource. The
objective function minimizes the total cost associ-
ated with recovering all flights in the stage under
consideration. The objective function is the summa-
tion of resources assignment cost, total delay cost
and cancellation cost. The first term in the objective
function is to recover open positions of each dis-
rupted flight by using the most efficient resources
in the system. The second and third terms promote
reliable operations by minimizing flight delay and
cancellation, respectively.

Constraints in (2) state that a resource cannot be
assigned to a flight if this resource is not available.
Constraints in (3) ensure that each available
resource is assigned such that it covers at most
one flight in the same stage. Constraints in (4)
ensure that if a flight is canceled ($L_f = 1$), no
resources are assigned to this flight. Also, if the
flight is not canceled ($L_f = 0$), the constraints ensure
that all positions of this flight are covered.
Constraints in (5) represent the qualification constraints.
For example, if a pilot and aircraft are covering the same flight $f$, the assigned pilot has to be qualified to fly the aircraft. The departure time of a flight is the maximum ready time among all its assigned resources as stated in Constraints (6). Constraints in (7) ensure that if a flight is delayed, there is no duty limit violation for any of its resources. Constraints in (8) relate the departure and arrival times for each flight. Constraints in (9) state that no flight is allowed to depart before its scheduled departure time. Finally, Constraints in (10) ensure that the decision variables $x$ and $L$ are binary variables and the flight departure and arrival times $(m_f, n_f)$ are integers.

7. Illustrative example

This section presents the application of DSTAR on a hypothetical airlines network of 8 stations and 51 flights. The example provides a description of how the tool works to recover an airline typical daily schedule. A time-space diagram of the network used in this example is given in Fig. 8. As shown in the Figure, each flight is shown by one arrow where the tail of the arrow is the scheduled flight departure time and the head of the arrow represents the scheduled flight arrival time. The daily schedule starts around 5 a.m. and ends some time after midnight, which represents the horizon of
Tables 1a–1c give the original aircraft routes, pilot trippairs and FA trippairs that cover the horizon of interest in this example, respectively. As shown in these tables, the entire schedule is covered by 14 aircrafts, 21 pilot trippairs and 25 FA trippairs. For simplicity and without loss of generality, all flights are assumed to use the same type of aircraft fleet and to have the same minimum crew requirements. One captain, one first officer and three FAs are the minimum crew requirement for each flight in the given network. In addition, each pilot trippair is built jointly for one captain and one first officer, and each FA trippair is built jointly for three FAs.

Now assume that stations “a” and “b” are subjected to severe weather conditions such that GDPs are issued at these two stations. In response to these GDPs, flight 12 is rescheduled to arrive at station “a” at 8:30 a.m., and flight 13 is rescheduled to depart from station “a” at 8:30 a.m. Also, flights 10 and 37 are rescheduled to arrive at station “b” at 9:30 a.m.

Running the simulation model, the list of disrupted flights is generated. Figs. 9a–9d shows the down-line impact associated with delaying flights 37, 12, 10 and 13, respectively. For example, when flight 37 is delayed, all flights on aircraft route 8, pilot trippair 11 and FA trippair 6 are added to the list of disrupted flights. Similarly, when flight 10 is delayed, all flights on aircraft route 4, pilot trippair 7 and FA trippair 3 are added to the list of disrupted flights.

The next step is to determine the start and end of the first recovery stage. Fig. 8 shows an aggregated representation of the boundaries of the different stages generated while running DSTAR over the entire horizon. As shown in the Figure, a flight is considered in a certain stage if the head of the arrow that represents this flight falls within the boundaries of this stage. Once the boundaries of the first recovery stage are determined, the optimization solver is activated to recover disrupted flights in this stage.

Disrupted flights in the first stage (stage zero) are flights 17 and 21, respectively. The results of the recovery model for stage zero are summarized as follows:

- Delay flight 17 until its resources out of flights 10 and 37 becomes ready. The new departure time of flight 17 is the greatest of the arrival time of flight 10 plus the aircraft service time, and the
arrival time of flight 37 plus the pilots’ connection time.

- Replace the two pilots on trippair number 9 with a stand-by captain and stand-by first officer. The new crew is assigned to flight 21, which is the first flight of the remaining portion of trippair 9.

No cancellation decisions are made at this stage. Flight 17 is a good candidate for delay as it affects only two down-line flights (26 and 34). Also, the use of standby pilots for flight 21 prevents propagating the impact to flights 42, 44, 45, 30, 25 and 47 as shown in Fig. 9b.

All resources are then updated based on the recovery actions taken in current stage. The new position of each resource is determined. In addition, the remaining legal duty period and the minimum required rest are calculated for each crew. Also, the maintenance items required for each aircraft in the system is updated based on the aircraft assignment in the current stage.

The results of the first stage are sent to the flight simulation model, which is again activated. Running the simulation model indicates that flights 26, 34, 33, 42, 44 and 45 are no longer on the disrupted list. Delaying flight 17 within its down-line slack allows its aircraft and pilots to be ready before the scheduled departure time of flight 26 and hence flight 34 is automatically recovered. Similarly, as flight 21 is assigned standby pilots, the outbound FAs become ready to serve flight 25. As flight 25 is scheduled to depart on time, all its down-line resources would be ready for flight 33. Thus, flight 33 is removed from the list of disrupted flights. Also, flights 42, 44 and 45 are getting their resources on time.

Dividing the remaining of the horizon into stages generates stage 1, which includes flights 13, 20 and 39. The recovery model is again activated to recover stage 1. The following summarizes recovery actions in this stage:

- Flight 13 is delayed until its aircraft and FAs out of flight 12 are available. The new departure time of flight 13 is the arrival time of flight 12 plus the
maximum of the required service time of the aircraft and the connection time for the FAs.

- Flight 39 is assigned reserve FAs. However, the only available FAs are assumed to be ready only after 30 minutes of the scheduled departure of flight 39. As such, a joint decision is made to delay flight 39 by 30 minutes to use the reserve FAs.

- Swap the resources of flight 20 with the inbound resources of flight 51. Once the resources of flight 50 arrive at station “b”, they are directly assigned to flight 20. The model swaps resources out of flight 51 with resources of flight 20 in order to prevent the delay of flights 6 and 24, respectively. Also, this enables the use of the down-line resources of flights 10 and 37 for flight 51 (if no more efficient resources are found at later stage).

The process continues to generate the next recovery stage in the system (stage 2). Running the flight simulation model indicates that flights 16, 19, 41 and 42 are the next disrupted flights to be recovered. The results of the recovery model at this stage are as follows:

- Flight 41 is delayed until all its inbound resources out of flight 39 are ready.
- Flights 16 and 19 are delayed until their inbound resources out of flight 13 are ready. Flight 16 is delayed until the aircraft becomes ready and flight 19 is delayed until the pilots and flight attendants connect out from flight 13.
- The standby captain and first officer that were assigned to flight 21 are assigned to fly flight 42 as well. This completes the required resources for flight 42.

The next run of the simulation model shows that flights 6, 24, 43 and 51 are the disrupted flights in recovery stage 3. Flight 6 uses resources out of flight 20, 16 and 5. As flight 16 is delayed in the earlier stage and this delay is within its down-line slack, its pilots would be available on time for flight 6. As flight 5 is projected to be on time, its FAs would connect on time for flight 6. After swapping the aircraft of flight 20 (aircraft 8) with the aircraft of flight 51 (aircraft 14), aircraft 14 would also used for flight 6. Therefore, flight 6 is recovered. Similarly, the aircraft and FAs of flight 16 would be ready with no delay for flight 24. Assigning the pilots of flight 20 (which was originally assigned to flight 51) to operate flight 24 completes all required resources for flight 24. Flight 43 is delayed until its aircraft out of flight 41 becomes ready. Also, the pilots of trippair 10 connect from flight 18 to flight 43. The delay of flight 43 causes no duty violation for its pilots. Finally, flight 51 uses the resources out of flights 10 and 37 (which would be ready before the departure time of flight 51) making this flight ready to depart on time.

Taking into consideration the results of previous stages, the simulation model is again activated. The results show that flight 46 is the only disrupted flight in stage 4. Running the recovery model indicates that flight 46 is delayed until its FAs become ready out of flight 43. The process continues showing that there are no more disrupted flights in the system. The delay of flight 46 is within its down-line slack allowing flight 48 to depart on time. Also, flight 32, and 34 have all their inbound resources ready on time. As the entire recovery horizon is scanned and no disrupted flights are found, the process terminates.

8. Application scenario

This section presents the application of DSTAR to develop a recovery plan for the schedule of a major US air-carrier during a hypothetical GDP scenario. In this scenario, 522 aircrafts, 1360 pilots and 2040 flight attendants are used to operate 1100 daily flights serving 112 cities. An early morning GDP with three impacted airports is assumed. The earliest ten flights that arrive at each of these airports are assumed to be issued control wheels-on times. The difference between a flight’s control wheels-on time and scheduled wheels-on time is generated randomly following a uniform distribution \( U[0, D] \), where \( D \) is the maximum delay in minutes.

In this GDP scenario, a maximum delay value of 100 minutes is assumed. It should be noted that GDPs that affect early morning flights, similar to the one considered in this example, usually result in severe downline disruptions as noted in Abdelghany et al. (2004c). For all experiments presented in this paper, an IBM personnel computer with 1.73 GHz processor and 512 MB of memory is used.

The flight simulation model is activated to capture the impact of this GDP on the entire schedule and to generate the list of disrupted flights. As explained earlier, a flight is considered disrupted if the flight’s predicted departure time is greater than its quoted departure time. Given the results of the simulation model, 177 flights are marked as dis-
rupted with 7633 total delay minutes. Fig. 10 illustrates an example of the delay propagation associated with including flight 0396 SEA-ORD 08 May 06:00 in the GDP. Flight assignments for each connecting resource that causes a downline disruption are also given. As shown in the Figure, the wheels-on control time for flight 0396 SEA-ORD 06-May 06:00 is 72 minutes beyond its scheduled one. This results in a misconnection violation for aircraft 38. Thus, the outbound flight 1202 ORD DTW 08 May 12:55 is projected a delay of 66 minutes. Flight 1202 ORD DTW 08 May 12:55 is the second segment of the first duty in Trippair N34 for FA 1394. The delay of this flight propagates through the rest of the segments in this duty resulting in delays of 45 and 42 minutes for flights 0343 DTW ORD 08 May 16:05 and 0103 ORD SNA 08 May 16:55, respectively. The delay of flight 0343 DTW ORD 08 May 16:05 causes a disruption in the route of aircraft 229 and thus it causes 58 minutes delay to the last flight scheduled for this aircraft on 08 May, which is flight 0275 ORD MCI 08 May 17:25. Flights on 09-May in the route of aircraft 229 are not impacted by this delay as the aircraft’s overnight slack time accommodates this delay. Finally, the delay of flight 0275 ORD MCI 08 May 17:25, which is the third segment in the first duty of Trippair N7, impacts the last segment in this duty. Thus, flight 0971 MCI DEN 08 May 19:44 is projected a delay of 32 minutes.

Given the list of disrupted flights resulted from this GDP, the recovery module is activated to recover these flights. In this scenario, all flights are assumed to have the same cancellation cost which is $400,000. In addition, a cost of $150 per 1 minute of delay is assumed for all flights. Resource swapping is allowed only if it saves 20 minutes or more of the projected flight delay. Furthermore, a good flight is included in a stage if it satisfies the following two conditions. First, the flight’s predicted departure time is equal to or less than the quoted departure time of a disrupted flight plus 20 minutes. Second, the good flight originates from the same station as the disrupted one. Deadheading options are not considered in developing this recovery plan. In addition, due to lack of data related to reserve resources, the results concentrate on presenting the model’s capability in finding the optimal resource swapping for delay saving. Whenever a crew duty violation is encountered and no optimal swapping among all operating resources is found to recover this duty violation, a standby crewmember is
assumed available to take over remaining segments in the violating duty.

The recovery process resulted in dividing the horizon into nine independent stages. Table 2 summarizes this process at the stage level illustrating number of disrupted and good flights considered, number of resource-swapped flights, number of uncovered flights, number of additional downline disrupted flights due to recovery action taken at the predecessor stage, delay saving and finally the stage running time.

As given in Table 2, no optimal recovery actions are considered in the first two stages as most flights in these two stages are part of the GDP program (i.e., flights with FAA’s issued control wheels-on time). The first stage in which a recovery action is identified is stage 3. In this stage, 32 disrupted flights and 26 good flights are included. Resources of flight 0858 SFO LAX 08 May 10:00 are swapped with resources of flight 0478 SFO DFW 08 May 10:45, which results in reducing the projected delay for the first flight from 55 minutes to 6 minutes and imposing a 10 minutes delay on the second flight. It should be noted that flight 0478 SFO DFW 08 May 10:45 is one of the good flights that is included in this stage. Furthermore, the delay of this good flight causes one downline flight to be added to the disrupted flight list. Table 3 illustrates the original and assigned resources to all positions of these two flights. The table also shows the ready time of all assigned resources and the new projected departure time for both flights after considering resources swapping. The originally assigned crewmembers to flight 0858 SFO LAX 10:00 have a ready time of 10:55, which is the predicted departure time of this flight. After swapping, the predicted departure time

<table>
<thead>
<tr>
<th>Stage</th>
<th>No. of disrupted flights</th>
<th>No. of good flights</th>
<th>No. of resource-swapped flights</th>
<th>No. of uncovered flights</th>
<th>No. of delayed flights in the entire horizon after recovering this stage</th>
<th>Delay saving in minutes</th>
<th>Running time of the stage in seconds</th>
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Table 3
Details of resources swapping in stage 3

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<th>Flight</th>
<th>Quoted departure time hh:mm</th>
<th>Predicted departure time hh:mm</th>
<th>Resource</th>
<th>The original flight of the newly assigned resource</th>
<th>Ready time of the assigned resource hh:mm</th>
<th>Projected departure time after swapping hh:mm</th>
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<td></td>
<td>Pilot – F/O</td>
<td>0478 SFO DFW</td>
<td>10:06</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>FA – FS</td>
<td>0478 SFO DFW</td>
<td>10:06</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td>0478 SFO DFW</td>
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<td>0858 SFO LAX</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>FA – M</td>
<td>0858 SFO LAX</td>
<td>10:55</td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td>FA – N</td>
<td>0858 SFO LAX</td>
<td>10:55</td>
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</tr>
</tbody>
</table>
is reduced to 10:06 which is the ready time of the newly assigned crewmembers. On the other hand, the new resources assigned to 0478 SFO DFW 08 May 10:45 are ready only at 10:55 which is the new departure time assigned to this flight.

No feasible recovery actions are found in stages 4 and 5. Another resource swapping occurred in stage 6. As illustrated in Table 4, flight 0937 IAD ORD 08 May 17:25 swapped its crewmembers with those of flight 0251 IAD PDX 08 May 18:05. Thus, the projected delay of the first flight is eliminated, while a 12 minutes delay is imposed on the second flight. Resource swapping introduced at this stage eliminates two projected downline flights from the disrupted flight list as presented in Table 2.

Stage 7 recorded the highest delay saving and also the highest number of resource swapped flights. A total delay saving of 582 minutes is recorded, which results from swapping the resources of 15 flights. Recovery actions considered in this stage reduces the number of disrupted flights to 172 flights. Table 5 illustrates the recovery actions associated with the largest flight delay savings occurred in this stage. Flight 0407 DEN SEA 08 May 17:20 is saved a delay of 89 minutes after swapping its aircraft with the aircraft of flight 1126 DEN DSM 08 May 18:30. This aircraft swapping results in 19 minutes delay for flight 1126 DEN DSM 08 May 18:30. It should be noted that flight 1126 was projected 10 minutes delay due to the late arrivals of its crewmembers.

No more feasible recovery actions are considered in the last two stages. Thus, the recovery module terminates with total delay saving of 661 minutes representing 8.70% of the total delay recorded in the corresponding do-nothing scenario. A total running time of about 36 seconds is recorded for this scenario.

9. Overall model performance

In this section, several experiments are conducted to illustrate the model’s overall performance in terms of solution quality and computation experience. The results of three sets of experiments are presented. The first experimental set investigates the effect of the relative values of the flight delay cost and resource swapping cost applied in the resources assignment module. The second set of experiments investigates the impact of the number of undisrupted flights included in each recovery stage on the solution quality and model performance. In the third set of experiments, the model is applied to recover the airlines schedule considering 16 different GDP scenarios. These GDPs differ in their severity, which is measured in terms of (a) number of impacted stations, (b) number of impacted flights at each station, (c) amount of delay assigned for each flight and (d) time of day at which the GDP is issued.

To improve the quality-of-life of its crewmember, airlines tend to minimize changing or modifying the crews’ originally scheduled trippairs, which they select at the beginning of every month. Thus, any recovery plan should carefully balance between achieved delay savings and number of swapped resources. Table 6 presents the effect of resource swapping cost on the overall performance of the

<table>
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<tr>
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<th>Quoted departure time hh:mm</th>
<th>Predicted departure time hh:mm</th>
<th>Resource</th>
<th>The original flight of the newly assigned resource</th>
<th>Ready time of the assigned resource hh:mm</th>
<th>Projected departure time after swapping hh:mm</th>
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<td>0937 IAD ORD</td>
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<td>Pilot – F/O</td>
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<td>FA – N</td>
<td>0251 IAD PDX</td>
<td>17:23</td>
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</tbody>
</table>
developed recovery plan. The swapping cost is represented as a multiple of the 1-minute delay cost. In this set of experiments, we assume a GDP scenario in which the 30 early flights to arrive at two of the airlines’ main hub stations are impacted. This GDP scenario impacts 176 downline flights with total delay minutes of 10,075. As shown in the table, generally, as the swapping cost decreases, the model is able to find better swapping opportunities with higher delay savings. For example, swapping cost that is equivalent to the cost of 5 minutes delay provides a recovery plan with 116 resource swapped flights and delay saving of 24.29% of the delay recorded in the corresponding do-nothing scenario. When the resource swapping cost is increased to be equivalent to the cost of 40 delay minutes, only two resource swapped flights are recorded and the delay saving is limited to 1.03%. On the other hand, less swapping cost generally increases the size of the problem search space and hence increases the model running time. A running time of 46.079 seconds is recorded for the case with least resource swapping cost. This running time decreases to 31.437 seconds when resource swapping is tightly constrained by setting resource swapping cost equivalent to the cost of 40 minute delays.

The effect of including undisrupted flights on the performance of the developed recovery plan is examined in the second set of experiments. As mentioned earlier, an undisrupted flight is included in a stage if this flight departs from the same station of any of the disrupted flights in this stage and its projected departure time is within a certain threshold of the disrupted flight’s quoted departure time. In general, longer threshold values result in adding more undisrupted flights in the recovery process. Three experiments with three different threshold values are considered. These values are 10, 20 and 30 minutes, respectively. The performances of the recovery plans generated in these three experiments are also

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Table 5
Details of resources swapping associated with the largest flight delay saving in stage 7

<table>
<thead>
<tr>
<th>Flight</th>
<th>Resource</th>
<th>The original flight of the newly assigned resource</th>
<th>Ready time of the assigned resource hh:mm</th>
<th>Projected departure time after swapping hh:mm</th>
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</thead>
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<td>Predicted departure time hh:mm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0407 DEN SEA 17:20</td>
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<td>FA – N 1126 DEN DSM</td>
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</tbody>
</table>

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Table 6
Effect of swapping cost on overall performance of schedule recovery

<table>
<thead>
<tr>
<th>GDP scenario description</th>
<th>Delay cost vs. swapping cost</th>
<th>Delay saving (%)</th>
<th>No. of flight with swapped resources</th>
<th>Final number of delayed flights</th>
<th>No. of stages</th>
<th>Running time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning GDP scenario, 30 GDP Flights, two hub stations, 176 impacted flights, 10,075-minute delay</td>
<td>1:5</td>
<td>24.29</td>
<td>116</td>
<td>195</td>
<td>13</td>
<td>46.079</td>
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<td>15.88</td>
<td>62</td>
<td>206</td>
<td>12</td>
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<td>3.69</td>
<td>21</td>
<td>184</td>
<td>10</td>
<td>35.031</td>
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<tr>
<td></td>
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<td>8.37</td>
<td>24</td>
<td>181</td>
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<td>35.672</td>
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<tr>
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<td>1:25</td>
<td>4.19</td>
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<td>177</td>
<td>9</td>
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<td>3.97</td>
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<td>178</td>
<td>9</td>
<td>31.797</td>
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<tr>
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<td>1.03</td>
<td>2</td>
<td>177</td>
<td>9</td>
<td>31.437</td>
</tr>
</tbody>
</table>
compared with a case where no undisrupted flights are included. The GDP scenario used above is used again in this set of experiments. As shown in Table 7, excluding undisrupted flights significantly limits opportunity for resource swapping and hence bounds the delay saving to 1.81%. When the threshold for including undisrupted flights is extended to 10 and 20 minutes, delay savings of 7.40% and 8.37% are achieved, respectively. Further extending this threshold to 30 minutes, a slight additional improvement of only 0.14% is achieved. Although the 30 minutes threshold allows more good flights to be included, ready times of these flights’ resources are expected to be greater than the quoted departure time of the corresponding disrupted flights. Therefore, these good flights are less likely to provide efficient swapping opportunities with the resources of the disrupted flights. It worth mentioning that, increasing the number of undisrupted flights results in slight increase in the model running time. A running time of 32.485 seconds is recorded when no good flights are included. The running time is increased to 36.347 seconds when the good flights threshold is set to be 30 minutes.

Table 8 summarizes the results of the third set of experiments, which is related to the GDP severity. The table presents the main parameters of each simulated GDP scenario and overall performance of the generated schedule recovery plan. GDPs are described in terms of number of impacted stations, maximum flight delay and time of day at which the GDP is issued. The total downline flight delays and number of impacted flights due to each GDP are also given. The schedule recovery plan is described in terms of the amount of delay saving, number of flights with swapped resources and total

### Table 7

<table>
<thead>
<tr>
<th>GDP scenario description</th>
<th>Threshold for including undisrupted flights</th>
<th>Delay saving (%)</th>
<th>No. of flight with swapped resources</th>
<th>Final number of delayed flights</th>
<th>No. of stages</th>
<th>Running time (seconds)</th>
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<tbody>
<tr>
<td>Morning GDP scenario, 30 GDP Flights, two hub stations, 176 impacted flights, 10,075-minute delay</td>
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<td>1.81</td>
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<td>32.485</td>
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<td>10 minute</td>
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<td>20 minute</td>
<td>8.37</td>
<td>24</td>
<td>181</td>
<td>10</td>
<td>35.672</td>
</tr>
<tr>
<td></td>
<td>30 minute</td>
<td>8.54</td>
<td>25</td>
<td>180</td>
<td>10</td>
<td>36.347</td>
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### Table 8

<table>
<thead>
<tr>
<th>No. of impacted hubs</th>
<th>No. of impacted flights</th>
<th>Maximum delay</th>
<th>Time of day</th>
<th>Initial number of delayed flights</th>
<th>Do nothing delay</th>
<th>Delay saving (%)</th>
<th>No. of flight with swapped resources</th>
<th>Final number of delayed flights</th>
<th>No. of stages</th>
<th>Running time (seconds)</th>
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<td>40 7 25.891</td>
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<tr>
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<td>11,367 5.88 24</td>
<td>182 9 32.797</td>
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<tr>
<td>1 30 150 Morning 179</td>
<td>11,367 5.88 24</td>
<td>182 9 32.797</td>
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<tr>
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number of delayed flights after recovery. As shown in the table, GDP scenarios are classified into four groups. The first GDP group studies the impact of GDP severity in terms of number of impacted flights at one of the airline’s hub station. GDP scenarios with 5, 10, 20 and 30 impacted flights are considered. Impacted flights in these GDP scenarios are the earliest flights to arrive at the impacted hub station, and the amount of flight minute delay is assumed to follow the uniform distribution \( U[0, 150] \). Generally, as the number of flights in a GDP increases, downline impacted flights and associated flight delays also increase. As shown in the table, in a GDP with only five delayed flights, 41 impacted flights and a total delay of 3425 minutes are recorded. As the number of flights in the GDP is increased to 30, 179 impacted flights and associated delay of 11,367 minutes are recorded. Flight delay savings and number of resource-swapped flights associated with the developed recovery plans are shown to be proportional to the amount of disputations in the schedule. A delay saving of 3.06% and 43 resource-swapped flights are recorded for the GDP with five impacted flights. For the GDP with 30 impacted flights, a delay saving of 5.88% and 182 resource-swapped flights are recorded. In addition, a running time in the range of half a minute is observed. This running time slightly increases with the increase in the size of introduced disruptions. One should also note that in two of the four tested GDP scenarios, the number of delayed flights after recovery increased. In other words, few good flights are slightly delayed to reduce longer projected delays of flights in the disrupted flight list.

In the second GDP group, the spatial impact of GDPs is studied. GDP scenarios with different number of impacted stations are considered. Thirty impacted flights are assumed to arrive at one, two, three and four hub stations, respectively. Impacted flights in this GDP set are the earliest flights to arrive at the impacted stations. In addition, flight minute delays in the simulated GDP scenarios are assumed to follow the uniform distribution \( U[0, 150] \). In general, no specific pattern of the size of schedule disruptions is observed. This is because the projected schedule disruptions depend mainly on flight connectivity at each of the impacted hub stations. The model was capable to develop efficient recovery plans with significant delay savings for the four simulated GDP scenarios. For instance, a recovery plan with delay saving of 9.79% and 191 resource-swapped flights is generated for the case when three stations are impacted by the GDP. This recovery plan is generated in a running time of 36.30 seconds.

The third GDP group examines the impact of time of day at which the GDP is issued. Four scenarios are considered. In all these scenarios, 30 flights that arrive at one station are assumed impacted by the issued GDP. The first scenario assumes that impacted flights are the first 30 flights to arrive at the impacted hub. Thus, it represents an early morning GDP. Second and third scenarios simulate noon and afternoon GDPs. The last scenario represents a GDP that occurs in the evening. Flight minute delays in this set of GDP are assumed to follow the uniform distribution \( U[0, 150] \). As expected, results indicate that GDPs that take place early in the day have severer disruption impact than those that occur later in the day. As illustrated in Table 8, the simulated morning GDP scenario results in delaying 179 flights with total delay minutes of 11,367 minutes. On the other hand, the evening GDP scenario leads to delaying only 67 flights with total delay of 4712 minutes. The recovery model successfully saves a larger proportion of the projected delay as the amount of this delay increases. In the morning GDP scenario, a delay saving of 5.88% is recorded. This percentage is reduced to only 2.10% in the evening scenario. As the size of schedule disruption decreases, the recovery model terminates in less time. A running time of 32.797 seconds is recorded for the morning GDP scenario, while a running time of 20.011 seconds is recorded for the evening GDP scenario.

The last GDP set examines the impact of the length of the control time delay. It assumes early morning GDP scenarios in which 30 flights at two stations are impacted. Flight minute delays in these scenarios are assumed to follow a uniform distribution \( U[0, D] \). The maximum delay value \( D \) is taken as 50, 100, 150 and 200 minutes, respectively. Shorter delay values are more likely to be absorbed by the flights slack time. Thus, as shown in Table 8, in the GDP scenario with maximum delay of 50 minutes, only 111 impacted flights and a total delay of 2041 minute are recorded. These values increases to 217 impacted flights and 19,998 delay-minutes in the GDP scenario with maximum delay of 200 minutes. The model generates recovery plan with significant delay savings for all simulated disruptions. For instance, a maximum delay saving of 8.37% is achieved in the GDP scenario of 150 maximum
delay minutes. One should also notice the relative increase in the running time required to generate the recovery plan. Sever GDPs result in higher number of disrupted flights and hence more running time of the recovery model. Nonetheless, all recovery plans are generated in less than 40 seconds.

10. Conclusions

In this paper, a decision support tool for airlines schedule recovery during irregular operations is presented. The tool allows airlines controllers to detect schedule disruptions ahead of their occurrence and to generate an integrated recovery plan for all used resources. A rolling horizon modeling framework with greedy optimization strategy is adopted. The framework integrates a schedule simulation model and a resource assignment optimization model. The flight simulation model predicts the list of disrupted flights in the system as a function of the severity of anticipated disruptions. The optimization model combines different recovery actions in one efficient plan to minimize projected flight delays and cancellations. A detailed example that illustrates the application of the tool to recover the schedule of a major US air-carrier during a hypothetical ground delay program scenario is presented. The results of several experiments that illustrates overall model performance in terms of solution quality and computation experience are also given. Based on these results, the tool was capable to generate an efficient recovery plan with considerable flight savings. Furthermore, all recovery plans are generated in less than 1 minute, which allows near real-time schedule recovery.

Several extensions are considered for this research work. First, through considering flight landing slots as one of the resources to be assigned for each flight, DSTAR could be extended to provide schedulers with an efficient slot allocation scheme as part of the Collaborative Decision Making (CDM) process adopted by the FAA. The resulting slot allocation scheme will ensure minimum system-wide disruptions. Furthermore, if information of airport gate availability is accessible, this information could be incorporated in the generated recovery plan. Developing a hybrid optimization strategy in which greedy resources assignment is modified to include look-ahead optimization capabilities is another extension. For instance, if an aircraft is scheduled for maintenance at some time in the future and this maintenance activity could be conducted in several stations. Feasible aircraft routes that end at all these stations could be generated. An aircraft assignment within a stage is marked feasible if it coincides along one of the generated routes. Thus, it ensures that local decisions made at each stage are resulting in a solution that satisfies maintenance constraints beyond the limits of this recovery stage.

References


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