Annals of Operations Research 127, 309–331, 2004

A Proactive Crew Recovery Decision Support Tool for Commercial Airlines during Irregular Operations

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Abstract. In this paper, a decision support tool that automates crew recovery during irregular operations for large-scale commercial airlines is presented. The tool is designed for airlines that adopt the hub-spoke network stru cture. The advance of this tool over the existing ones is that it recovers projected crew problems that arise due to current system disruptions. In other words, it proactively recovers crew problems ahead of time before their occurrence. In addition, it gives a wide flexibility to react to different operation scenarios. Also, it solves for the most efficient crew recovery plan with the least deviation from the originally planned schedule. The tool adopts a rolling approach in which a sequence of optimization assignment problems is solved such that it recovers flights in chronological order of their departure times. In each assignment problem, the objective is to recover as many flights as possible while minimizing total system cost resulting from resource reassignments and flight delays. The output of this tool is in the form of new crew trippairs that cover flights in the considered horizon. A test case is presented to illustrate the model capabilities to solve a real-life problem for one of the major commercial airlines in the U.S.

Keywords: airlines, irregular operations, crew recovery, proactive recovery, integer programs

1. Introduction

Planners at commercial airlines make all the effort to efficiently schedule profitable flights and allocate them the necessary resources (aircraft, crew, and flight attendants). In most large commercial airlines in the U.S., the airline network is built using the hub-spoke structure. A hub is a station with high flight departure and arrival rate for the airline. On the other hand, a spoke represents a station that is served by a few daily departures/arrivals. Each airline usually selects several stations to serve as hubs. Following this structure, each flight operated by the airline starts and/or ends at one of these hubs. Departures and arrivals at hubs are grouped in time banks in which each set of arrivals is followed by a set of departures to allow smooth connection for crew and passengers. This hub-spoke network structure allows the airline to serve more passengers between most cities by traveling through one of its hubs.

During daily operation, several irregularity sources could erupt causing disruptions to the planned schedules. Examples of irregularity sources include adverse weather conditions, unexpected aircraft breakdown, sick crew, etc. Due to the tight connection among airline resources, these disruptions could dramatically propagate over time and space unless the proper recovery actions are taken. For example, if a crewmember were delayed at a particular station such that she/he misconnects her/his next flight, this flight and all consequent flights assigned to this crewmember would have a crew shortage problem. However, if this problem is identified ahead of time, an efficient recovery solution could be generated to avoid further down-line flight delays and/or cancellations.

Crew recovery during irregular operation is usually subjected to a set of conflicting constraints. For example, crew recovery plans have to fully comply with the governmental regulations set to ensure safe airlines operation. Violating these regulations subjects the airline to severe fines. Similarly, since the airline industry is heavily unionized, labor unions in agreement with the airline specify crew operation rules such as labor service times, training requirements, compensations, etc. Recovery plans have to comply with these labor agreements as well. In addition, recovery plans should consider any possible operating cost increase and/or revenue cut. Using expensive recovery actions like ferrying an aircraft, rebook passengers on other airlines increases operating cost and reduces expected revenues. Furthermore, the customer side of the operation should be considered. Frequent flight delays and cancellations lessen service reliability, which could result in customers' goodwill loss. Finally, recovery actions for crew should be compatible with recovery actions taken for other resources in the system. For example, it is not acceptable to assign a crewmember to a flight that she/he is not qualified for its aircraft.

In most commercial airlines, the recovery process is performed independently for each resource through three different groups (desks). Usually, aircraft recovery gets the highest priority, then crew, and finally, flight attendants. Coordination between the decisions of the three groups is made through a fourth group (controllers), which makes sure that all resources are available for each flight in the schedule. Usually, the crew desk performs the crew recovery process manually. The members of the crew desk are trained on some ad-hoc rules to follow while preparing a recovery plan during irregular operation. They are also well informed about the governmental regulations and labor agreements so that they do not violate any of them while preparing the recovery plan. However, during massive system disruption, due to the large-size of the problem and the complexity involved in applying these regulations and agreements, an efficient error-free manual crew recovery of the schedule becomes a challenge and very time consuming process.

Most of the crew scheduling literature has focused on the planning phase of the problem. A general overview of this literature can be found in Etschmaier and Mathaisel (1985), Gershkoff (1989), and Barnhart et al. (1999, 2002). However, little attention has been given to the problem during the operation phase. Johnson et al. (1994), which represents one of the early researches in this area, presented a methodology for crew rescheduling during irregular operation that is only limited to solve a single misconnection. Teodorovic and Stojkovic (1995) developed a sequential approach for crew reassignment using a dynamic programming algorithm in which the objective is to minimize the ground time of the crew. Wei and Yu (1997) presented a system-wide multicommodity integer network flow model in conjunction with a heuristic search algorithm. One of the features of their model is that it incorporates operation constraints such as number of impacted flights and number of modified trippairs to bound the solution.

However, the crew on one flight is treated as one commodity travelling together, which is practically not a general rule. Stojkovic, Soumis, and Desrosiers (1998) solved a model that modifies personalized planned monthly assignments of airline crew during day-to-day operations. The problem is formulated as a set-partitioning problem, and a column generation method embedded in a branch-and-bound search tree has been implemented to solve it. Lettovsky, Johnson, and Nemhauser (2000) presented a solution framework that provides a recovery plan for crew reassignment to restore the disrupted schedule in almost real time. Preprocessing techniques are applied to extract a subset of the schedule for rescheduling. A fast crew-trippair generator is then applied to enumerate feasible continuations of partially flown crew trippairs.

In this paper, a decision support tool that automates crew recovery during irregular operations for large-scale commercial airlines is presented. The model is designed for airlines that adopt the hub-spoke network structure. The advance of this tool over the existing ones is that it recovers projected crew problems that arise due to current system disruptions. In other words, it proactively recovers crew problems ahead of time before their occurrence. Also, it provides the required flexibility to react to the different operation scenarios. In addition, it solves for the most efficient crew recovery plan with the least deviation from the originally planned schedule (minimizing delay and cancellations) and the planned workload of the crew. This is achieved by using reserve crew, swapping workloads between crew, and crew deadheads. The tool adopts a rolling approach in which a sequence of optimization assignment problems is solved such that it recovers flights in chronological order of their departure times. In each assignment problem, the objective is to recover as many flights as possible while minimizing total system cost resulting from resource reassignments and flight delays. The output of this tool is in the form of new crew assignments (known as trippairs) that cover flights in the considered horizon.

This paper is organized as follows. Section 2 presents a description of the airline operation and discusses the effect of current business practice on crew problems and their recovery. Section 3 gives a formal definition of the crew recovery problem addressed in this paper. Section 4 presents the methodology and the solution approach including the mathematical formulation of the problem. Section 5 shows an example of applying the model for a real world problem for a major airline company in the United States. Final notes and conclusions are given in section 6.

2. Airline operation description

2.1. Crew problems

Crews are usually classified based on their qualification and experience to three positions ranked from the highest as captain (CAP), first officer (F/O), and second officer (S/O). Each crewmember is qualified and trained to fly certain fleet type, and she/he cannot fly any other fleet at any circumstances. In hub-spoke network structure, crew schedules are typically set in what is known as trippairs. Each trippair consists of a sequence of flights

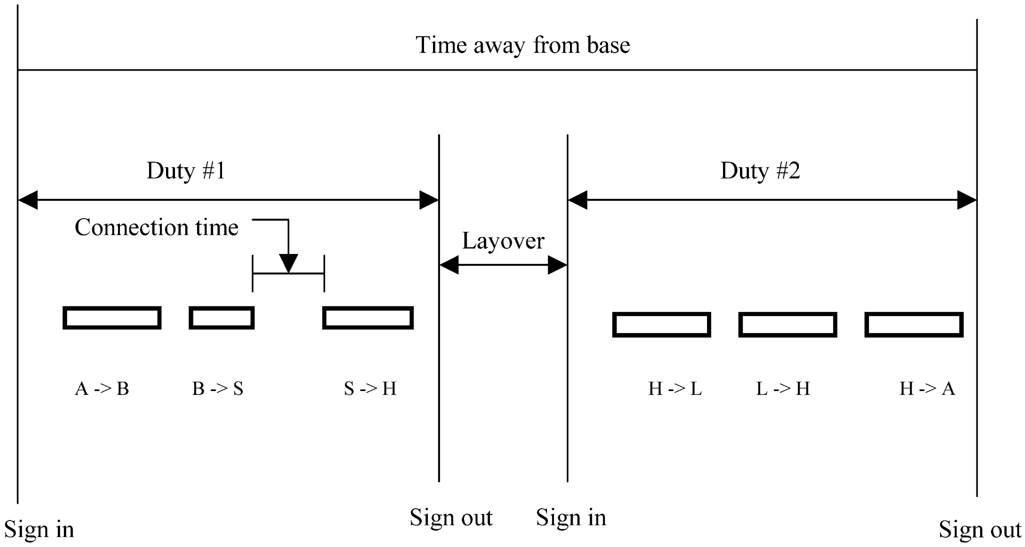

Figure 1. A typical crew trippair in normal operation conditions.

(segments), the first of which starts at the crew domicile (home base) and the last ends at this domicile. Each segment consists of a single take off and landing, with no intervening stops. A trippair typically extends over two to five days and consists of a successive set of duty periods and rest periods (layover). Figure 1 shows a typical 2-day trippair that starts and ends at station A and has a layover at station H. The duty period starts about one hour (briefing period) before the departure time of the first segment on the duty period and ends about 15 minutes (debriefing period) after the arrival time of the last segment of the duty period. The lengths of the duty and the rest periods are determined based on the governmental regulations and the union agreements to 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 equal to or greater than the minimum connection time at this station. This connection time allows a crewmember to move to the departure gate of the next segment, if it is different from the arrival gate of the current segment. Trippairs are built for the whole month for the different crew positions and fleets, forming lines of trips. These lines are usually published two to three months before their starting date. In most major U.S. airline companies, crewmembers bid on these lines based on their seniority to choose the most convenient trippair that matches their positions and qualifications.

As mentioned earlier, due to the irregularity that could happen during operation, schedules could get disrupted such that crew no longer follows their planned schedules (trippairs). Due to these disruptions, different possible crew problems can occur, which can be defined as follows.

Misconnect problem. It occurs when a connecting crewmember arrives late such that she/he is unable to fly the next flight, in the same duty period, on time. Figure 2 shows

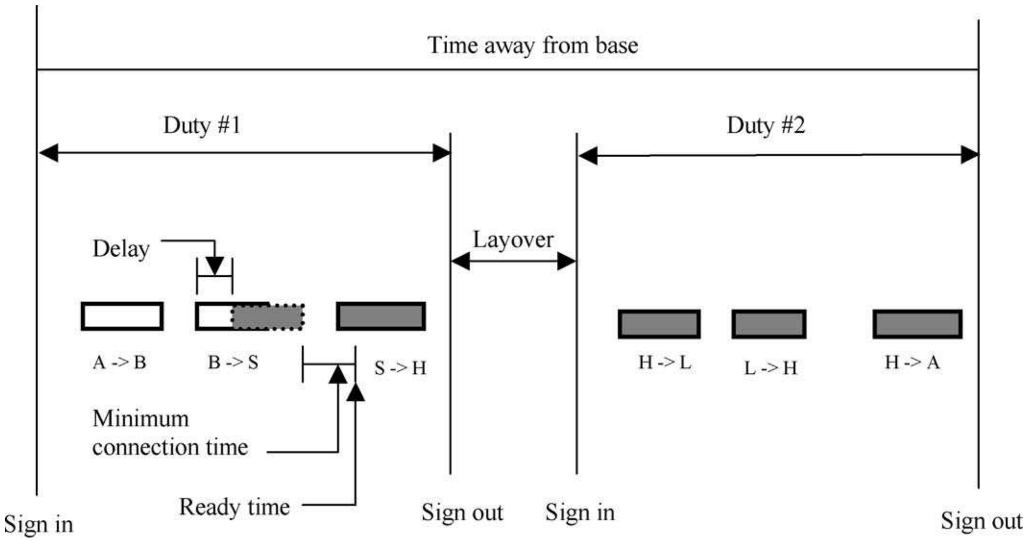

Figure 2. Example of misconnect problem.

an example of a typical misconnect problem. When flight B–S is delayed, the new connection time became less than the minimum required connection time for the crew. Therefore, another crewmember should be found at station S for the next flight (S–H) in order to depart on time.

Rest problem. It occurs when a crewmember gets a rest period (layover) that is less than the minimum required rest period. This could be due to late arrival at the end of the previous duty period. In this case, the crewmember would be unable to fly the first segment of the next duty period on time. This problem is a special case of the misconnect problem by considering the required rest period as the required connection time. Figure 3 shows a typical example of the rest problem. When flight S–H is delayed, the layover becomes less than the minimum required rest period. The first flight of the next duty period (flight H–L) cannot depart on time by the originally assigned crew, since the crew has to get the minimum legal rest at station H.

Duty problem. It occurs when a duty period limit is exceeded due to a delay for one or more of the flights of this duty period. This delay could be due to ground holding, unplanned aircraft maintenance, longer unexpected customer service time, etc. In this case, the crew cannot fly the last flight(s) of the duty period, due to this duty problem. Figure 4 shows a typical example of a duty problem. Flight S–H is delayed and its arrival time passes the duty limit of the crew. Therefore, another crew should be found at station S to fly flight S–H.

Unassigned problem. It occurs in case of no show for a crewmember due to cancellation of her/his inbound flight or any other possible reason such as calling sick.

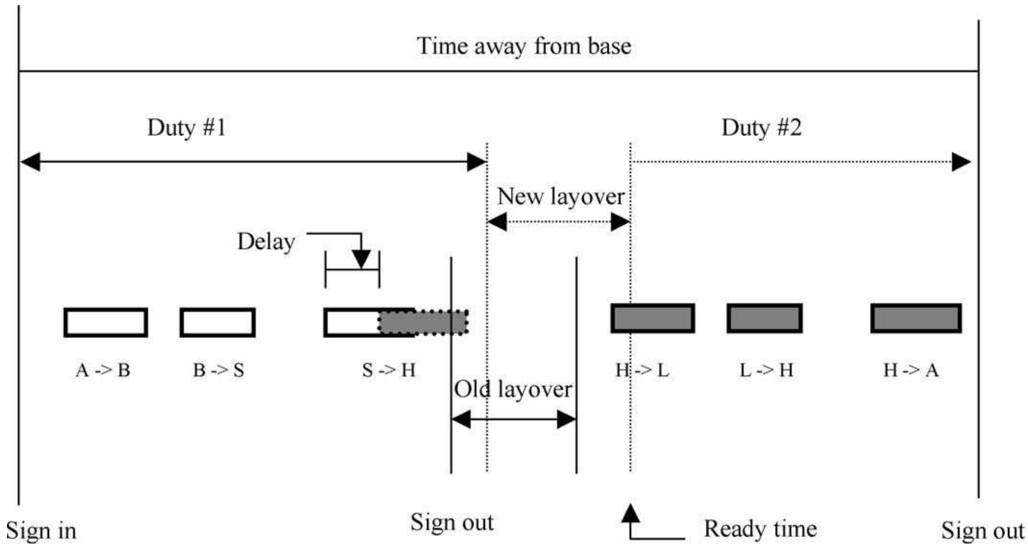

Figure 3. Example of rest problem.

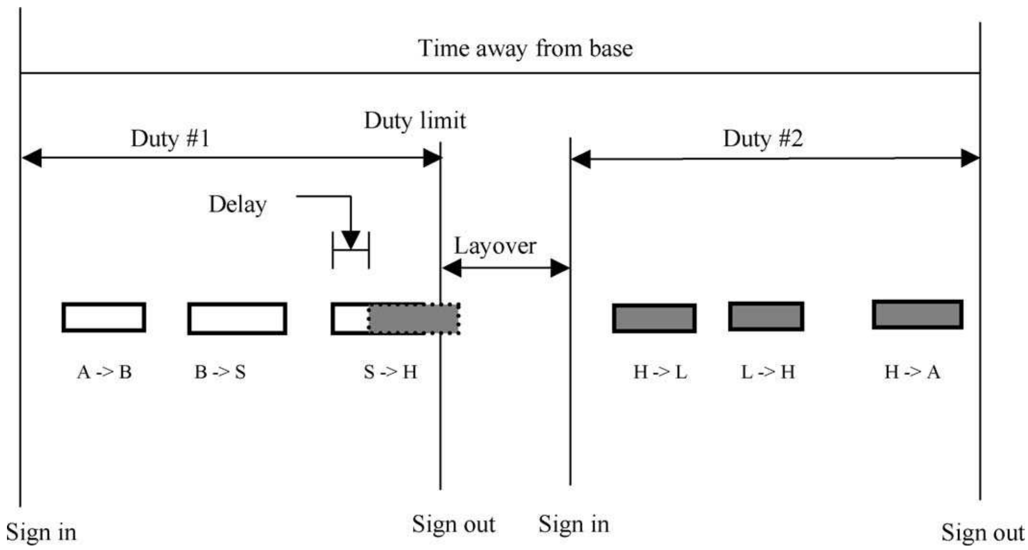

Figure 4. Example of duty problem.

It should be noted that if a duty problem occurs, its crewmember would not be able to fly any segment that has arrival time beyond the duty period limit. This means that there is no chance that this crewmember can fly the remaining portion of her/his trippair as it was originally planned. On the other hand, a misconnecting crewmember or crewmember with rest problem may still be able to fly the remaining part of the trippair, if delaying the subsequent flight(s) is acceptable. However, if the proposed

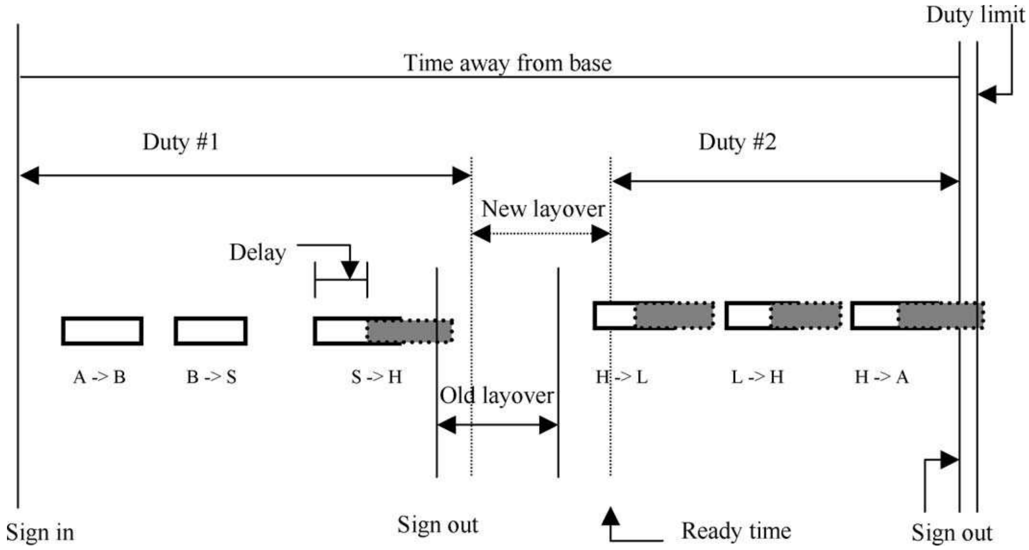

Figure 5. Example of projecting crew problems.

delay is greater than the operationally accepted delay or if this delay would cause a crew duty violation, this crewmember will not be able to fly the remaining portion of her/his trippair and another crewmember should be found.

2.2. *Projecting crew problems*

Tracking system resources and their down-line flights can project the possible effects of a certain disruption of one of these resources on planned crew schedules for several hours in the future. For example, consider the two-day trippair of a crewmember shown in figure 5. Assume that the last flight of the first duty period (flight S–H) is delayed due to unscheduled aircraft maintenance. Tracking the effect of this delay can project the possible future crew problems of this trippair. For instance, due to this delay, the crewmember would arrive late at station H and her/his layover will be less than the minimum required rest. Since, the crewmember cannot fly the next morning flights unless she/he takes the minimum required rest, the first flight of the second duty period (flight H–L) has to be delayed as shown in figure 5, or another crew has to be found to fly it on time. Therefore, the crew problem (rest problem) of flight H–L can be projected just when the flight S–H is delayed, which is several hours before the scheduled departure time of flight H–L. Also, if no crew is found to fly flight H–L and it is delayed, its subsequent flights L–H and H–A will be delayed as well. Since the delay of flight H–A will cause it to arrive after the duty period limit of the crewmember, a duty problem could be expected at the origin of flight H–A. Considering delaying flight H–L, the duty problem can be projected at the time when flight S–H is delayed, which is almost one day before the scheduled departure time of flight H–A. Knowing crew problems ahead of time is very advantageous to the recovery desk as it gives the chance to proactively deal with these potential problems trying to avoid them or to reduce their downline impact.

2.3. Recovery actions

Generally, several actions are available for the crew recovery desk to recover crew problems. These actions include:

Delaying (re-quoting). A flight can be delayed to wait for its connecting crew or until its original crew gets their required rest period. Also, if a new crew is assigned to this flight, the flight can be delayed until the new recovery crew gets ready.

Using stranded crew. Crewmembers that are stranded at stations due to cancellation or misconnecting their next flights can be used as recovery crew for any other crew problems at these stations. They can also be deadheaded to other stations where they can get new assignments.

Crew swapping. During system disruption, crewmembers of the same qualification can exchange their jobs. In this case, an earlier flight with crew problem is covered with the crew of a later flight with the condition that the crew of the problem flight will be able to fly this later flight.

Deadheads. A crewmember can be deadheaded from a station to cover an open flight at another station. The crewmember can be deadheaded on a flight for the same airline or on other airlines. In general, crewmembers can be deadhead to be repositioned at any station or returned to their domicile.

Using standby crew. Standby crewmembers are positioned at the major stations and ready to substitute any other crewmember that cannot fly her/his flight.

Using reserve crew. Reserve crewmembers are positioned at their homes and ready to work after a predefined time interval to cover any open flight(s). This predefined interval is usually set to allow the crewmember to get ready and get a transport to the airport.

If a crew problem is encountered, these actions are investigated to determine their feasibility for recovering this crew problem. The main challenge for the crew recovery desk is how to prioritize the use of these actions to solve several problems, at the same time, in the most efficient way. It is usually hard to determine the impact of using a certain recovery action on the system operating cost. However, a general cost-efficient order of these actions can be as follows. First, a delay within an acceptable threshold (0–14 minutes) is expected to have the minimum cost impact. This delay recovers most misconnect and rest problems and usually has little down-line effect on the system. This small amount of delay is expected to be absorbed in the down-line slacks (the difference between the actual connection time and the minimum connection time) between flights. Second, using the stranded crewmembers is another inexpensive option.

These crewmembers might be stranded due to cancellation or misconnection of their down-line flights. The pay of these crewmembers is usually guaranteed whether they flew these cancelled/misconnect flights or not. Adding different flights instead of the cancelled/misconnect ones adds no cost to the cost of operation. Third, if no stranded crew is available, one can use other undisrupted (good) crewmembers in the system for swapping purposes. Similar to the previous option, no cost is added to the cost of operation when changing the schedules of undisrupted crewmembers. The only disadvantage is that those undisrupted crewmembers might dislike changing their original schedules, resulting in quality of life issues. Standby/reserve crewmembers are used for the most hard-to-recover problems. The use of standby/reserve crew has to be minimized whenever possible for two main reasons. First, using these crewmembers for flying usually adds to the operating cost, since they have to be compensated for flying according to their contracts. Second, schedulers should keep standby/reserve for possible unseen future crew problems. Finally, longer delays or flight cancellations would be the last option available to deal with crew problems.

It should be noted that actions taken by the crew recovery desk to recover crew problems might change from instance to another, depending on the system status and the available recovery options. It is generally expected that, in case of massive system disruption, when many crew problems take place, the crew recovery desk might be willing to allow more flight delays to recover flights and save standby/reserve crew for more serious problems. Also, if the crew recovery desk faces shortage of standby/reserve and swapping options, more delays might be introduced in the system. On the other hand, if standby/reserve and swapping crewmembers are available, the crew recovery desk will be willing to use them to minimize the number of delayed flights.

2.4. Effect of network structure on crew problems and recovery actions

As mentioned earlier, in most large commercial airlines in the U.S., the airline network is built using the hub-spoke structure. Since hubs are having more activities (higher flight departure and arrival rate) for the airline, there is higher chance that crew problems will take place there. Therefore, commercial airlines set most of their standby/reserve resources at these hubs to easily recover the disruptions that might erupt at these hubs. In general, crew problems can be classified into two classes. The first are problems that occur at spokes and the second are problems that occur at hubs. Usually, there are not many options to solve crew problems at spokes. In most cases, flights that have crew misconnect or rest problem at the spoke are delayed until its original crewmember arrives or finishes its layover rest. If a duty problem occurs at a spoke, the flight is usually cancelled, as its crewmember cannot violate their duty period limit. The other option to solve crew problems at spokes is to deadhead another crewmember on another airlines to the spoke to fly the problem flight. This second option usually needs to be done manually to check seat availability for the deadheaded crewmember on other airlines. Deadheading crewmembers on the same airlines to the spoke is usually a rare option, as there are few flights for the airline serving the spoke. As for the hub-located problems, they are usually easier to solve, as there are more several options available. First, standby/reserve crews that are located at the hubs can recover crew problems there. In addition, since the hub station usually has many arrivals and departures for the airlines at the same time bank, there is usually good chance for crew swapping at the hub station. Finally, recovery crew can be deadheaded on the same airlines from another hub to recover crew problems. As such, it is generally easier to recover crew problems that occur at hubs than crew problems at spokes.

3. Problem definition

The list of trippairs with anticipated crew problems is given as input. Each trippair is defined by its number, crew position, fleet type, sequence of flights, and the first flight at which the crewmember would be disrupted. In addition, a snap shot of the current airline schedule is given as an input to the model. This is represented in terms of the list of flights scheduled by the airline. Each flight is defined by its number, origin, destination, scheduled departure/arrival times, and estimated departure/arrival times (if a delay is anticipated). Given also are the workloads of crewmembers defined in terms of their current trippairs. The list of standby/reserve crew at each station is also given. For each crewmember, the following information is defined: crew position, domicile, fleet type, ready time, duty limit, required rest, and the maximum remaining time away from base. The horizon at which crew problems are to be considered is also give. Only crew problems that are within this horizon will be considered. The cost of assigning a particular crewmember to a flight is also given. Finally, the cost of one-minute delay of a flight is also given.

Available crews that could be used in the recovery process include standby/reserve crews, stranded crews that cannot complete their original assignment but could be reassigned to new tasks, and finally good crews that could be swapped to cover other broken trippairs. Two main operational constraints control the use of these crewmembers. First, crew assigned to operate a flight must be qualified for this flight and be compatible with other resources assigned to the flight. For example, if an aircraft of certain fleet is assigned to a flight, crewmembers that are assigned to the same flight have to be qualified to fly this fleet. Second, crewmembers should comply with all mandatory operation rules set by the government and the union agreements. For example, if a flight is delayed, this delay should cause no violation to the crew duty limits or the rest requirements. All regulations and crew agreement rules that govern the operation of the different resources are assumed given. These rules include crew legal rest requirements and crew duty period limits. The objective is to develop an efficient recovery plan to fix all disrupted flights in the horizon such that the total system cost resulting from crew reassignments and flight delays is minimized. This recovery plan is developed in terms of new crew trippairs that covers all flights in the horizon under consideration.

4. Solution approach

The approach adopted in the crew recovery tool invokes a sequence of optimization assignments to cover flights in chronological order of their departure times. Figure 6 shows the whole framework for the crew recovery tool. As shown in the figure, the implementation consists of four main steps defined as data input, preprocessing, optimization solver, and the post-processing. A detailed description of figure 6 and the different steps of the algorithm are given below.

4.1. Data input

The following is given as input to the model:

- The list of trippairs with anticipated crew problems (each trippair is defined by its number, crew position, fleet type, sequence of flights, and the first flight at which the crewmember would be disrupted).
- A snap shot of the current airline schedule, represented in terms of the list of flights scheduled by the airline (each flight is defined by its number, origin, destination, scheduled departure/arrival times, and estimated departure/arrival times).
- The workloads of crewmembers defined in terms of their current trippairs.
- The list of standby/reserve crew at each station.
- The following information is defined for each crew member: crew position, domicile, fleet type, ready time, duty limit, required rest, and the maximum remaining time away from base.
- The horizon at which crew problems are to be considered.
- All mandatory operation rules set by the government and the union agreements that govern crew operation.

4.2. Preprocessing

Figure 6 presents different preprocessing steps as follows.

4.2.1. Shift problems to hubs

Some crew problems that are expected to occur at a spoke have the special characteristic that they can be shifted to occur at the preceding station (which is usually a hub). In other words, if the problem is happening at a spoke, it can optionally be solved at a hub. To illustrate let us consider the following duty problem example. Consider a trippair that consists of two duty periods as shown in figure 7. The second segment of the second duty period is ending at a hub while the third segment is ending at a spoke. Assume that the second segment of the second duty got delayed as shown in case 2, which consequently delays all remaining flight segments in this duty period. Assume that the crewmember on this trippair will exceed her/his duty time limit due to this delay, if she/he flies the last segment of the duty period. This means that this crewmember should stop flying at the

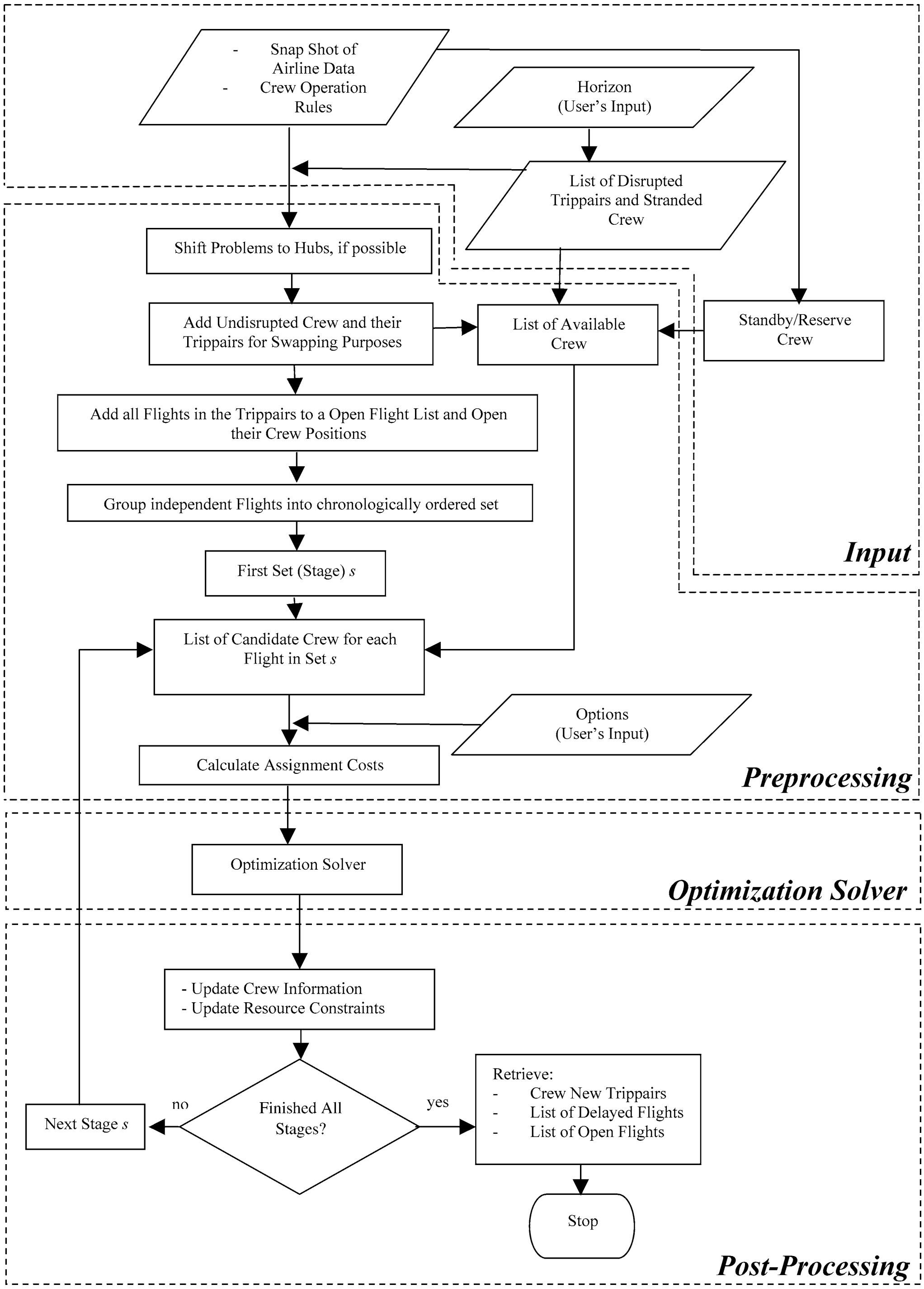

Figure 6. Crew recovery tool framework.

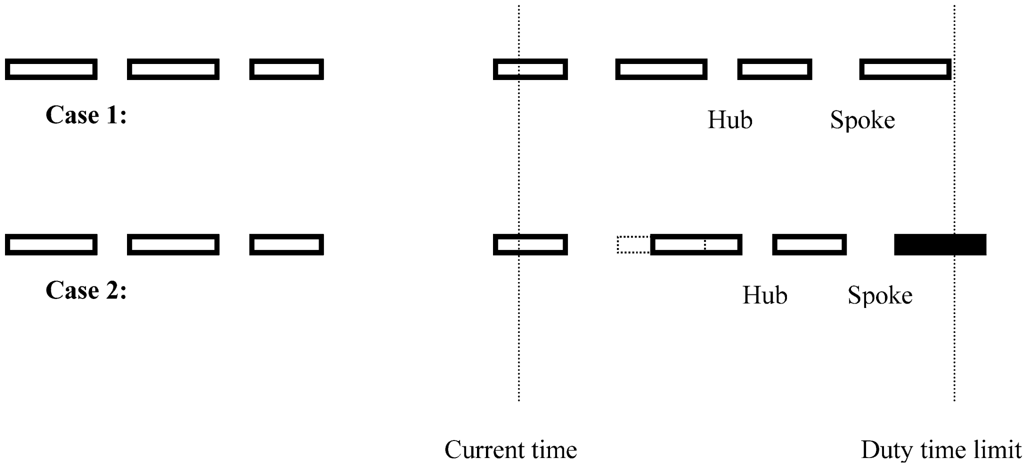

Figure 7. Example of shifting a duty problem to a hub.

spoke and another substitute crewmember should fly this last segment. As mentioned earlier, finding recovery crew at spokes is usually difficult. Also, having a stranded crewmember at a spoke is not a good option, as it is usually not easy to use her/him efficiently or return this crewmember back to her/his domicile. However, if we know at the departure time of the second segment that the crewmember will exceed her/his duty time limit, he/she could be asked to stop flying at the hub (the destination of the delayed flight). Then, another recovery crewmember is found at the hub to fly the remaining segments of the duty period or the remaining part of the trippair. To take advantage of this characteristic of the hub/spoke network structure, all crew problems that are happening at spokes are shifted such that they will be starting at the hub, whenever possible. As such, these crew problems are treated as if they are starting at the hub stations and a recovery crew is searched to operate all remaining flights starting at this hub station.

4.2.2. Add undisrupted crew and their trippairs for swapping options

The list of undisrupted (good) crewmembers that can operate the first open flight in the disrupted trippairs are identified. This is performed for the possibility of swapping their assignments with the assignments of the originally disrupted crews. For example, assume a trippair that is disrupted due to misconnection of its crewmember A at station H. Assume also that flight f1 is the misconnect flight that is departing from station H. To find the swapping options at station H to fly flight f1 on time, any undisrupted (good) crewmember B that is arriving at station H before (or after by a reasonable amount of delay) the scheduled departure time of flight f1 and is qualified to fly flight f1 is identified. Then, crewmember B is considered as a candidate to fly flight f1. If crewmember B has any assignment at station H such as flight f2, crewmember A could be considered as a candidate for flight f2 if she/he arrives at station H before the scheduled departure time of flight f2.

It should be noted that finding crewmembers for swapping purposes is only performed for the first open flight in the disrupted trippairs. This is mainly due to two main reasons. First, the first open flight is usually the most difficult flight to recover. It is noticed that if a crewmember is found to fly the first open flight in the disrupted trippair, she/he can continue flying the subsequent flights in the trippair. Second, disrupting good crewmembers for each flight in the disrupted trippair will unnecessarily increase the problem size and consequently the solution time, which is unfavorable.

4.2.3. Prepare set of available crew

All crewmembers that are available in the system and could be used in the recovery process are grouped in one set. This set includes: (1) crewmembers that are stranded at any station due to some disruption in their schedule. These crewmembers might be able to work on other flights or need to be returned to their domiciles. Also, all co-pilots of these stranded crews are included in the set. The reason to include the good co-pilots of the stranded ones is to be able to reassign these crewmembers to other flights if their original flights are cancelled or given to another crew. (2) Crewmembers who are disrupted on-purpose for swapping options, as defined above. (3) The set of standby/reserve crew. For each crewmember in the set, the following information is defined: crew position, domicile, fleet type, ready time, duty limit, required rest, and the maximum remaining time away from base.

4.2.4. Flight chronological ordering and grouping

The flights in the partial trippairs of the set of crewmembers defined above are then grouped in sets as shown in figure 8. Each set includes flights that are resource independent. 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 depart from two different stations at the same time, it would be operationally infeasible for these two flights to feed resources to each other. On the other hand, by definition, two flights in the same crew trippair are not resource independent. An earlier flight in the crew trippair feeds resource(s) to any subsequent flight in the same trippair. Each of these sets defines a recovery stage. The start of a 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. These stages are ordered chronologically based on their start times. It could be argued that the chronological order of stages does not allow the case of using a resource for a later flight without checking the possibility of using this resource for an earlier flight. In other words, it is not guaranteed to keep a crewmember idle in one stage to assign it to a particular flight f in a future stage. The crewmember could be used to fly any flight in an earlier stage and she/he will not be able to fly flight f. However, as airline is dynamic and uncertain system, it is not practically recommended to keep a crewmember idle and not to use it for an encountered problem, waiting for a crew problem that might occur in the uncertain future. The operation priority is to fix earlier problems in the system con-

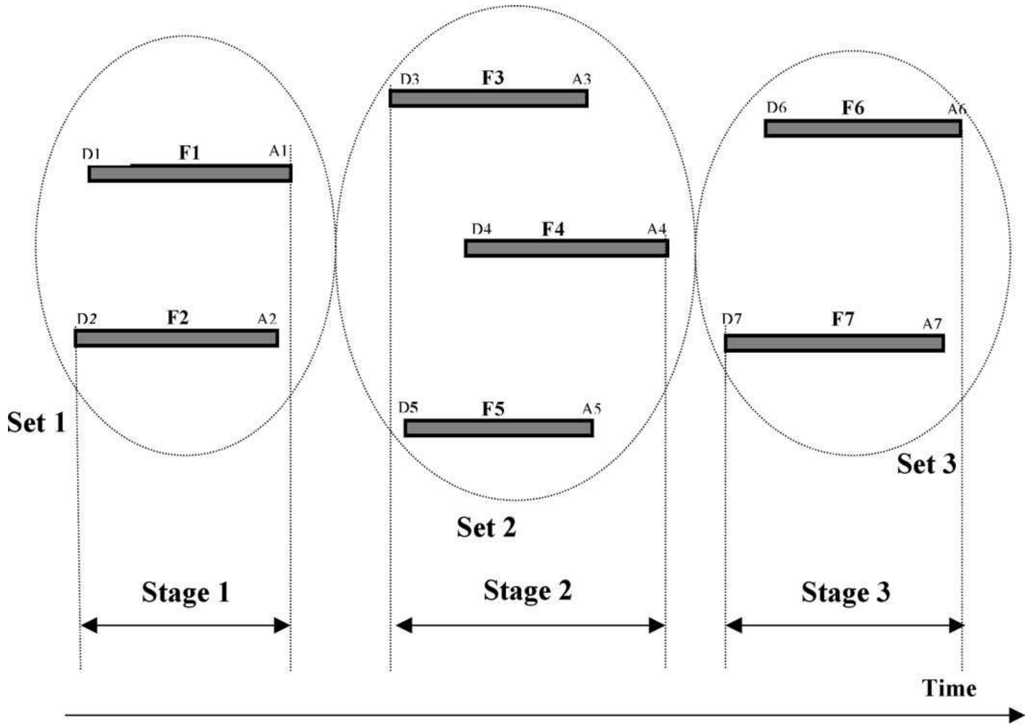

Figure 8. Sets of independent flights.

sidering all available resources, and worry later about other future uncertain problems, which is the approach followed in presented methodology.

4.2.5. Candidate crew

Having defined the sets of resource-independent flights and the bank of available crew in the system, the set of candidate crewmembers that could be assigned to each of the flights in the first set is defined out of the whole set of available crew. The reason for screening candidate crewmembers for each flight is to minimize the size of the assignment problem. A particular crewmember is defined to be a candidate for a flight if she/he satisfies the following conditions: (1) the crewmember has the same position and fleet as those of the flight, (2) the crewmember is arriving at the flight origin before the flight's departure time plus the maximum allowed delay, and (3) after adding the flight to her/his previous flown flights, the new assignment does not violate any of her/his contractual rules and regulations. I.e., the crewmember does not exceeds her/his duty limit and the crewmember does not exceeds the maximum time away from base. Once a crewmember satisfies the above conditions, she/he can be defined as a candidate for the corresponding flight. It should be clear that, as a result of the preprocessing step, a particular crewmember could be simultaneously candidate for more than one flight in the same flight set.

4.2.6. Assignment cost calculations

The next step is to determine the assignment cost for each candidate-flight pair. The assignment cost is modeled such that it meets different operation conditions such as minimizing deviation from the original schedules, minimizing the use of standby and reserve resources, reducing amount of deadheads in the system, minimizing adverse down-line impact, and minimizing the idle time of the resources in the system.

This assignment cost is typically function of the following terms.

Swap cost. A cost is added if the candidate crewmember is to be moved from its originally planned trippair to cover a flight in another trippair.

Standby/reserve cost. A cost term is added if the candidate crewmember is a standby or reserve. This cost will be added based on how much using standby/reserve crew is to be penalized.

Deadhead cost. A cost term is added if the candidate crewmember is deadheaded from another station to origin of the open flight. This cost will be added based on how much deadhead is to be penalized.

Idle time cost. A cost term is added for every minute that the candidate crewmember would remain idle, if she/he is assigned to the open flight.

Down-line cost. A cost is added to take into consideration the down-line impact of a crew-flight assignment. This down-line cost measures how a crewmember would be able to fly the subsequent flights in the trippair. In other words, it evaluates the usability of the crewmember downline the newly assigned flight (e.g., can complete the remaining flights in the new trippair without delays or not). This cost is represented in terms of the down-line delay that will result in due to the assignment and a penalty term to be added if the crewmember is to be stranded away from his domicile.

4.3. The optimization model

The preprocessing steps divide the whole horizon into consecutive recovery stages. Each stage includes a list of open flights. A list of crew recovery candidates is also defined for each flight in the recovery horizon. The objective of the optimization model presented in this section is to efficiently assign the candidate crewmembers to the open flights at each stage. The problem is formulated mathematically in the form of a Mixed Integer Program (MIP) as given below.

Define:

F: total number of flights,
i: an index for a flight that needs to be recovered,
k: an index for crew position (CAP, F/O, S/O),
j: an index for an available crew in the system,
h: an index for a hub station in the system,
x_{ikj}: $= 1$, if crewmember j is assigned to position k on flight i and $= 0$, otherwise,

a_j: the ready time of crewmember j,
c_{ikj}: cost of assigning crewmember j to position k on flight i,
c'_i: cost of one-minute delay of flight i,
t_i: scheduled departure time of flight i,
m_i: departure time of flight i,
n_i: arrival time of flight i,
b_i: block time of flight i,
v_j: duty limit for crewmember j,
d_{ij}: $= 1$, if crewmember j is deadheaded to operate flight i, and $= 0$, otherwise,
S_{hk}: the maximum number of standby/reserve crewmembers of hub station h and position k to be used in the current stage,
DD_k: the maximum number of undisrupted (good) crewmembers of position k that change their originally assigned trippairs and work on another trippair in the current stage,
DH: the maximum allowed deadheads in the current stage,
SS_k: the set of standby/reserve crew of position k,
D_k the set of undisrupted (good) crewmembers of position k.

Objective function:

$$\text{Minimize } \sum_i \sum_j \sum_k c_{ikj} x_{ikj} + \sum_i c_i [m_i - t_i]$$

subject to:

$$\sum_j x_{ikj} = 1 \qquad \forall i, k, \tag{1}$$

$$\sum_i \sum_k x_{ikj} \leqslant 1 \qquad \forall j, \tag{2}$$

$$m_i - a_j x_{ikj} \geqslant 0 \qquad \forall i, j, k, \tag{3}$$

$$m_i - t_i \geqslant 0 \qquad \forall i, \tag{4}$$

$$n_i \leqslant v_j x_{ikj} \qquad \forall i, j, k, \tag{5}$$

$$\sum_i \sum_k \sum_{j \in S} x_{ikj} \leqslant S_{hk} \qquad \forall h, \tag{6}$$

$$\sum_i \sum_k \sum_{\substack{j \in D_k \\ j \neq \text{original crew of } i}} x_{ikj} \leqslant DD_k, \tag{7}$$

$$\sum_i \sum_k \sum_j d_{ij} x_{ikj} \leqslant DH, \tag{8}$$

$$n_i = m_i + b_i \qquad \forall i, \tag{9}$$

$$x_{ikj} = \{0, 1\} \qquad \forall i, j, k, \tag{10}$$

$$m_i, n_i \geqslant 0 \qquad \forall i. \tag{11}$$

The objective function minimizes the total cost of assigning crewmembers to flights and the associated delay, if any. The first term in the objective function tries to recover open crew positions on each flight by using the most efficient crewmembers in the system. The second term promotes a reliable operation as it minimizes the total flight delay. Constraint (1) ensure that each open crew position on each flight is assigned to a crewmember. A dummy crewmember will be used if no real crewmembers are found for this open position. If a flight is assigned to the dummy crew, this flight will be reported as an open flight in the final solution. The crew recovery desk might decide to cancel this flight or try to find other recovery options that are not investigated by the model such as deadhead crew on other airlines, change equipment, etc. Constraint (2) ensure that a crewmember is used to cover at most one open position or otherwise no flight is assigned to this crewmember. If a crewmember remained without an assignment in one stage, her/his information is updated such that she/he could get an assignment for a flight in subsequent stages. The departure time of a flight is the maximum ready time among all its assigned crewmembers as stated in constraint (3). Constraint (4) state that no flight departs before its scheduled departure time. Constraint (5) ensure that if a flight is delayed, there is no duty limit violation for any of its crewmembers. Constraint (6) control the number of standby/reserve crewmembers to be used at each hub. Constraint (7) controls the number of swaps of the undisrupted (good) crewmembers in the solution. Constraint (8) controls the number of deadheads in the solution. The set of constraints (6)–(8) give the flexibility to control the different resources in the system. For example, if no standby/reserve crewmembers are available while solving a particular problem, the right-hand side of constraint (6) is set to zero. Similarly, the number of good crewmembers that can be reassigned to work on another disrupted trippair can be controlled through the right-hand side of constraint (7). Similarly, deadheads can be controlled through the right-hand side of constraint (8). The right-hand sides of constraints (6)–(8) are updated after each stage to reflect the remaining resources that still can be used in successive stages. For instance, if it is initially specified that (10) standby/reserve crewmembers are to be used in the solution and (2) of them are used in the first stage, the right-hand side of constraint (6) is updated to (8) for the next stage. Constraint (9) state that the arrival time of the flight is equal to it departure time plus its block time. Finally, constraints (10) and (11), respectively, ensure that the assignment decision variables are binary variables and the flight departure and arrival times m_i and n_i are nonnegative.

4.4. Post-processing

Based on the result of the assignment model, a crewmember is assigned only to the open flight in the stage under consideration. Decision on the remaining part of the broken trippair is left to successive recovery stages. In other words, the crewmember is assigned only to the first flight of the broken trippair and waits for next stages to finalize the assignment decisions. This enables the chance to improve the solution using other resources that might appear in the system at later stages. It also enables a crewmember to resume its original workload, if it is found to be a good candidate in a subsequent stage. As shown in figure 6, at the end of any stage and based on the recovery decisions made in this stage, crew information is updated by determining the new position of the crewmember, new ready time, new duty limits, remaining time away from base, and the required rest. The required rest after each duty is calculated based on the flying hours in the last 24 hours and the start of the duty. This information represents the input for the next recovery stage in the horizon. Once all the stages are scanned, the output of the optimization solver in every stage is retrieved. This output is used to generate new crew trippairs that covers all flights in the open flight list. Also, the list of all re-quoted flights and the list of all flights that were not recovered are generated.

5. Test case

In this section, a test case for the crew recovery tool is presented. The test case represents crew problems that took place in the schedule of one of the major airlines in the U.S. on a day of summer 2002. All problems are projected using another tool that projects the effect of the current system status on future system conditions. The detailed description of this tool is beyond the scope of this paper. In summary, its objective is to estimate the possible departure/arrival times of flights based on current updated system status. Then, these estimated departure/arrival times are used to generate the different crew problem described in section 2. The list of crew problems that are projected to occur based on the condition of flights in the next 8 hours period starting at 10:00 AM is given. Those problems are given in the form of crew trippairs. Each trippair is defined in terms of the original crewmember on the trippair, problem type, trippair number, trippair starting date, position, fleet type, domicile, and the slack. This slack reflects the problem significance. In case of duty problems, it shows by how much a crewmember would violate her/his duty if she/he continues flying her/his trippair. In case of misconnect problems, it shows how long the next flight would be delayed such that the misconnect crewmember would be able to catch it. Finally, in case of rest problems it shows how much the next flight would be delayed until the crewmember gets her/his required rest. A total of 18 crew problems are considered. Seven of them are misconnection, two are duty problems, and the remaining nine are rest problems. These problem trippairs are for CAP and F/O crew positions and four different aircraft fleets (I, II, III, and IV). Each problem trippair is defined also in terms of its flights (segments). For operational data storage limitations, flights that are starting two days before the date of the test are not included, so the complete trippair is not necessarily given for all problems. Each flight is represented by its number, origin, destination, a flag indicating whether or not the flight is starting at a hub station, and scheduled departure/arrival times. In addition, each flight in the trippair is given an indicator (problem indicator) to indicate whether this flight is the first problem flight in the trippair. The first problem flight has a problem indicator of 0. Flights that are before the first problem flight in the trippair have a problem indicator of -1 and flights that are after the problem flight have a problem indicator of 1. As mentioned earlier, whenever possible, spoke problems are shifted at the previous hub. This means

Table 1
Values of model parameters.

Parameter	Value
Maximum allowed delay for a flight due to pilot (minutes)	60
Cost of deadhead compared to the cost of a delay of 1 minute	20
Cost of assigning standby-reserve crew compared to the cost of a delay of 1 minute	25
Cost of swap compared to the cost of a delay of 1 minute	23
Maximum standby/reserve at H1 to be used in the solution	3
Maximum standby/reserve at H2 to be used in the solution	3
Maximum standby/reserve at H3 to be used in the solution	3
Maximum standby/reserve at H4 to be used in the solution	3
Maximum standby/reserve at H5 to be used in the solution	3
Maximum deadheads to be used in the solution (not including the deadhead needed at the end of trip to return crewmembers to her/his domicile)	6
Maximum number of good crewmembers that can change their original trippair to work on another trippair	10

that a good flight that precedes the problem flight could be included in the solution. For this reason, another indicator (consider indicator) is given to show the flights that are assigned to its original crewmember before running the solution (consider indicator = Y) and the flights that are considered in the problem (consider indicator = N).

Table 1 shows the list of parameters used to solve the given problems. As shown in this table, the maximum allowed delay for a flight is 60 minutes. This means that no crew will be considered as a candidate for a flight if her/his ready time is greater than the scheduled departure time of the flight by more than 60 minutes. The cost of deadheading a crew to work on a flight is 20 times the cost of 1-minute of its delay. This means that delaying a flight for 20 minutes is as good as deadheading a crewmember to fly it on time. Similarly, the cost of assigning a standby/reserve crew to a flight is 25 times the cost of 1-minute of its delay. Also, the cost of taking a crewmember out of her/his trippair to work on a flight in another trippair is considered to be 23 times the cost of 1-minute of its delay. The maximum of standby/reserve crewmembers at each of the hubs that can be used in the solution does not exceed 3. Also, the maximum number of deadheads that can be used in the solution does not exceed 6. This number does not include the deadhead needed at the end of trippair to return crew to their domiciles, if needed. Finally, the maximum number of undisrupted (good) crewmembers that can be taken out of their original trippair to work on another trippair does not exceed 10. It should be noted that the values used at this table are for illustrative purposes only. Users are given the capability to change the value of these parameters to reflect any recovery objective and different operation scenarios. For example, if no delay is required during the recovery process, user can reduce the deadhead cost, the cost of swapping, and the cost of using standby/reserve crewmembers and rerun the model. If the solution is still not satisfying in terms of the obtained delay, users can reduce these costs again and rerun the model. Although, these parameters are easy to change and the implications of their change are straightforward, their change should be done with caution, as they will significantly affect the quality of the obtained solution.

The total number of crewmembers included initially in the problem based on the preprocessing step is 121. These pilots include 18 stranded, 17 standby crewmembers, 52 reserve crewmembers, and 34 undisrupted crewmembers. The solution is obtained using the CPLEX® callable library solver. The solution is given in the form of comparing the old and new workloads of the different crewmembers before and after the solution. Each crewmember is defined by her/his ID, problem type, original trippair, starting date of the original trippair, position, fleet type, domicile, and the slack of the original trippair. The old workload is given in terms of the flights in the original trippair. Each flight is defined by a deadhead indicator ($DH = 1$ if deadhead flight and 0, otherwise), flight number, origin, destination, scheduled departure/arrival times, and the problem and the consider indicators defined above. The new workload is given in terms of the new flights given to the crewmember. Each flight is defined by deadhead indicator, flight number, origin, destination, suggested departure/arrival times, flight delay, and finally the original trippair of the flight.

The model suggested that the first two crewmembers, who have duty problems will not fly their last flight in the duty and trippair. Otherwise, the model suggested that they take rest at their current station and deadheaded on the next day to their domicile. Two standby crewmembers from the current station will fly this dropped flight and then be deadheaded back to their domicile. To solve two of the rest problems, the model suggested that the morning flight is to be delayed such that these two crewmembers take the required rest. This delay is found to have no down-line impact on the crew schedules. Similar delay decisions are taken to solve another two rest problems. For two crewmembers with rest alerts of -90 minutes slack, the model decided that these crewmembers do not fly their morning flights. No substitute crewmembers are found for the trippairs of those crewmembers and their flights will remain open. This is because the required delay is more than the maximum allowed delay set for the problem. It worth mentioning that when the model solution is checked against what the schedulers did to solve this crew problem, it is found that schedulers did not find any other solution to this problem other than re-quoting the departure time of the morning flight. In other words, the morning flight was delayed for 90 minutes.

For another two rest alerts with -72 minutes slack at a spoke, the trippair was originally planned such that the two crewmembers have a round rip consists of the last flight in the current duty and the first flight of the next duty and a layover at a spoke. The model suggested that the two crewmembers do not fly their last flight in the duty period to not to be stranded at the spoke and drop this round trip from their schedule. In other words, the model suggested that the two crewmembers are to be hold at the origin of their last flight in the duty, which is a hub station, and continue flying from the second flight of the next duty period. At the same time two standby crewmembers will fly the dropped round trip. One of these two standby crewmembers is found at the hub station and the second one is deadheaded from another hub to fly the round trip and deadheaded back to his/her domicile.

To solve one misconnection problem of crewmember, a swap had to take place between the misconnect crewmember and an undisrupted (good) crewmember. Four flights

Table 2
Solution summary.

Problems:	
Total number of problems in the system	18
Total number of Misconnect	7
Total number of Duty	2
Total number of Rest	9
Run time:	
1 minute 51 seconds	
Deadhead:	
Total number of Intermediate Deadhead Flights introduced	2
Total number of Deadheads required at the end	6
Swaps:	
Total number of Swaps used in the run	6
Swaps involving Misconnect	0
Swaps involving Duty	0
Swaps involving Rest	0
Swaps involving Good pilots	1
Swaps involving Pilots available from Cancellations	0
Swaps involving Standby and Reserve pilots	5
Standby/reserve:	
Total number of Standby pilots used	4
Total number of Reserve pilots used	1
Open positions:	
Total number of segments left open in the system	8 (4 flights)

are removed from the trippair of the misconnect crewmember and added to the trippair of the undisrupted crewmember. At the same time, three flights are removed from the trippair of undisrupted crewmember and added to the trippair of misconnect crewmember. Then, a deadhead flight is added to the trippair of the undisrupted crewmember to make her/him catch the remaining of her/his trippair. Also, a reserve crewmember is called to fly a flight dropped from the trippair of the undisrupted crewmember and then he is deadheaded back to his domicile. Finally, delaying the down-line flight(s) solves the other problems of misconnection crewmembers, which was found to be the optimum solution based on the model input.

As shown in table 2, it took the model less than 2 minutes on HP B.11.00 U 9000/800 system. The total number of deadheads in the solution is 8. Four standby crewmembers and one reserve are used. Only one undisrupted (good) crewmember is taken out of his original trippair for swapping purposes. Finally, 4 flights remained open.

6. Conclusions

In this paper, a decision support tool that automates crew recovery during irregular operations for large-scale commercial airlines is presented. This tool is designed for airlines that adopt the hub-spoke network structure. The advance of this tool over the existing ones is that it recovers projected crew problems that arise due to current system disruptions. In other words, it proactively recovers crew problems ahead of time before their occurrence. Also, it gives a wide flexibility to react to the different operation scenarios. In addition, it solves for the most efficient crew recovery plan with the least deviation in the schedule from the originally planned one. The tool adopts a rolling approach in which a sequence of optimization assignment problems is solved to recover flights in chronological order of their departure. In each assignment problem, the objective is to recover as many flights as possible while minimizing total system cost resulting from resource reassignments and flight delays. The output of these assignment problems is used to generate new crew trippairs that covers flights in the considered horizon. Also, the list of all re-quoted flights and the list of all flights that were not recovered are generated.

The main limitation of this model is that it is missing information on other resources in the system such as aircraft and flight attendants. It is believed that a global recovery plan for the three resources (aircraft, crew, and flight attendants) should be obtained simultaneously due to the required connection between them. For example, if a flight were missing a crewmember and a flight attendant, a recovery plan for the flight attendant would be of no use, if the crew position were not recovered. A research effort to consider a global recovery tool for the three resources at the same time is underway by the authors. Second, solving flights in chronological order prevents the model from having the whole picture of the down-line flights, which precludes obtaining a global optimum solution. However, considering the huge number of constraints imposed on the operation recovery process, the associated uncertainty, the need to generate the recovery plan in real-time, test experiments conducted by the tool shows that the heuristic implemented in this tool generates solutions at high level of satisfaction to the tool's users.

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