Solving Airline Crew Scheduling Problems by Identifying the Existence of Crew Swaps

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Abstract. We investigate a problem for solving airline crew recovery problem efficiently. We present a concept to identify the candidate crew swaps in the operation of airline crew schedules. We show that crew recovery problem can be solved by canceling disjoint cycles in crew routes. Moreover, candidate crew swaps can also be obtained by finding all possible crew routes that can be constructed from active flights. The existence of a directed cycle in crew networks will inform to us how to swap crew routes. Based on these properties, we propose an algorithm for swapping crew. The computational results show that the algorithm can be implemented to solve crew recovery problems in short period of time.

Keywords: Crew Recovery, Crew Swap, Flight Delay, Cycle.

Introduction

Airline schedules are operated under uncertain conditions. Several factors such as high aircraft traffics, bad weather condition, and aircraft failure often disrupt schedule operations. During disruptions occur, a number of flights might be delayed or cancelled. Since one flight delay could induce delay propagations, airlines need to re-schedule flight operations in short period of time.

Typically, airlines recover their crew schedules from disruption by performing recovery actions such as deadheading, swapping crew or delaying flights. Swapping crew is a recovery action that allows active flights to operate as the planed schedules. Since passenger satisfaction is important for airline, swapping crew will be selected first, if it is a possible action. Moreover, swapping crew will reduce complexity in solving airline crew recovery problem.

In this paper, we present a proof of concept to find crew swap opportunities by identifying cycles in crew routes. We show that rerouting crew assignment can be done by canceling the disjoint cycles in crew routes. Moreover, cycle on crew routes can be used to identify the existence of crew swaps. Based on our findings, we construct an algorithm for swapping routes. We implemented the algorithm to solve crew recovery problems on a number of flight delay cases. The computational

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results show that the proposed algorithm can solve crew recovery problems efficiently.

The ideas to use swaps as the first priority action in airline recovery have been investigated by several authors. Ageeva [1] derived a model of aircraft schedules which can be easily recovered in irregular operations. The schedules were designed to include many cycles in order to obtain routes which are easy to swap. A multi objective model to rerouting aircraft that allow retiming flights was proposed by Burke et al. [2]. The idea for retiming flights is also investigated in [3]. Eggenberg [4] presented a model of aircraft recovery problem by considering uncertainty as the constrains. Novianingsih et al. [5] proposed a method for solving airline crew recovery problems heuristically. The method worked by performing crew swaps in first stage. Ilagan and Sy [6] constructed a crew swap model to find swap opportunities for crew assignment during disruptions. Rosenberger et al. [7] developed an optimization model to reroute aircrafts. Unlike Rosenberger et al. [7] who developed an efficient method for selecting aircraft swaps, our research focus in solving airline crew recovery problem by finding the possibility of crew swaps. Our approach on identifying crew swaps is almost similar to research in [6]. While Ilagan and Sy [6] found crew swaps by solving an optimization model, we perform crew swaps after identifying cycles in two crew routes.

The outline of this paper is as follows. In Section 2, we discuss airline crew recovery problems. The concepts concerning our approach to solve the problem are discussed in Section 3. Computational results are given in Section 4. In Section 5, we present some concluding remarks.

2 Airline Crew Recovery Problem

Disruptions on airline schedule operations could induce several problems. During the disruptions, a number of flights could be delayed or cancelled. Since the connecting time between two flights will reduce when one flight is delayed, the delay might propagate to disrupt the operation of other flights. The delays can also lead the reduced period for crew to take a rest. As a results, crew will experience a rest problem or a duty problem. Crew will lose their connecting flights if one flight in their route is cancelled. Other crew problems can be found in Abdelghany et al. [8].

Airline schedule disruptions could dramatically propagate over schedule networks. To minimize the effects of disruptions in schedule operation, recovery actions should be performed by airlines during schedule disruptions. Airlines might delay some flights or cancelled flights to solve the connecting problems. Deadheading should be executed for returning crew to their base. Rerouting assignments might be implemented to avoid a number of flight delays. We call crew that exchange their flight assignments as crew swaps.

Disruptions could lead to the planned crew routes became infeasible. To solve this problem, airlines should provide new flight routes for crew if one flight is delayed. In Novianingsih et al. [5], the new crew routes can be constructed by identifying active flights firstly. Then, we find all possible crew routes that can be formed using the active flights. In the last step, the route with minimum cost will be assigned to each active crew. However, solving a new crew assignment in airline recovery is not easy and it often needs a long period of time. Several authors have been proposed how to solve airline crew recovery problems efficiently (see [9–14]).

Let F be a set of flights. Let dep_i and arr_i be a departure and arrival airport of flight f_i, respectively. Let $dept_i$ and $arrt_i$ be a departure and arrival time of flight f_i respectively. A sequence of flight $r=\{f_1,\ldots,f_n\}$ is called as a flight route if $arrt_i < dept_{i+1}$ and it maintains flow balance; that is for $f_i \in F$, $arr_i = dep_{i+1}$, $i=1,\ldots,n-1$. We call a flight route as a feasible crew route (pairing), if the route complies with the FAA's and airline's rules. A feasible crew route stars and ends at a specific airport that we call as a crew base. There is minimum required connecting time between two consecutive flights in a feasible crew route. Total flight hours of crew in a day are limited by maximum flight time. After crew finished their flight assignment in one route, they will get a rest for minimum required rest period. The detail explanations about the rules can be found in AhmadBeygi et al. [14].

3 Main Results

Consider a flight route $r=\{f_1,\ldots,f_n\}$. A sub route $\{f_i,\ldots,f_j\}$ in r is called as a cycle if $arr_j = dep_i$. Table 1 shows an example of two flight routes, and we found one cycle in Route 1 i.e $\{2,3\}$ and four cycles in Route 2 i.e $\{5,6\}$; $\{6,7\}$; $\{8,9\}$; $\{6,7,8,9\}$. It is obvious that every cycle includes at least two flights. If we remove cycle $\{2,3\}$ in Route 1, we obtain a new flight route $\{1,4\}$ which maintain flow balance. The following propositions explain the characteristic of a cycle in r.

Table 1. Example of routes.

Flight	Route 1		Flight	Route 1	
	Departure airport	Arrival airport		Departure airport	Arrival airport
1	A	B	6	B	A
2	B	C	7	A	B
3	C	B	8	B	E
4	B	D	9	E	B
5	A	B			

Proposition 1. *If π is a cycle on r, then π - r maintain flow balance.*

Proof: Let $r=\{f_s,\ldots,f_t\}$ be a cycle on r, where $1<s<t<n$. Then, there exists $l \geq 1$ and $k \leq n$ such that (f_l,f_s) and (f_t,f_k) are connecting flights in r. Now, we can write r as $r=\{f_1,\ldots,f_l,f_s,\ldots,f_t,f_k,\ldots,f_n\}$. Hence, $\pi - r = \{f_1,\ldots,f_l,f_k,\ldots,f_n\}$. Since (f_l,f_s)

and (f_l, f_k) are connecting flights in r, we obtain that $arr_l = dep_s$ and $arr_l = dep_k$. Since we also know that $\{f_s, \ldots, f_t\}$ is a cycle on r, it follows that $arr_t = dep_s$. As a result, we have $arr_l = dep_k$, and finally π - r is a flight route. The proof is completed.

Let π and π' be disjoint cycles on r, i.e π and π' do not contain the same flights. Then, we will obtain the following corollary as the consequence of Proposition 1.

Corollary 1. *If α is a disjoint cycle on r, then π - α is a flight route.*

Corollary 2. *If r is a feasible route for crew k, then π - α is also a feasible route for crew k.*

Given R_k^0 as an initial feasible route for crew k. We call a route s maintains original ordering if every pair of flights f_i, f_j in s which are constructed from flights in the initial route, f_i precedes f_j in s for $i < j$. Let $F_k^0 := \{f \in F | f \in R_k^0\}$ be a set of flight in R_k^0. Let $\mathfrak{R}_k^F$ be a set of feasible routes of crew k that can be constructed using flights F and maintain the original ordering. It is clear that $R_k^0 \subseteq \mathfrak{R}_k^{R_k^0}$. Beside R_k^0, the feasible routes of crew k can also be obtained by applying Corollary 2. So, the number of the feasible routes will be the same with the number of disjoint cycles on R_k^0. Now, we can rephrase Corollary 3 as follows.

Corollary 3. *If Γ is a disjoint cycle on R_k^0, then.* $\left|\mathfrak{R}_k^{F_k^0}\right| = \begin{cases} |\Gamma|, & R_k^0 \subseteq \Gamma \\ |\Gamma| + 1, & otherwise \end{cases}$.

Let C be a set of crews. For $k_i, k_j \in C$, we define $O_{k_i k_j} := \mathfrak{R}_{k_i}^{F_{k_i}^0 \cup F_{k_j}^0} - \mathfrak{R}_{k_i}^{F_{k_i}^0}$. Then, $O_{k_i k_j}$ defines a set of feasible routes for crew k_i that contains at least flight in $F_{k_j}^0$. Consider a directed graph $G = (C, E)$, where $E = \{(k_i, k_j) | O_{k_i k_j} > 0\}$. The graph indicates that if $(k_i, k_j) \in E$, then there exists a single crew swap k_i to crew k_j. For $k_i \in C$, $1 \le i \le m$, let R_{k_i, k_j} be a set of a single swapping route for crew k_j and crew k_i. Let FP_r be a set of fights which are contained in r. The following proposition guarantee the existence of a crew swap between two crew.

Proposition 2. *Let $M = \{k_i, k_j, k_i\}$ be a directed cycle on G for any $k_i, k_j \in C$, $i \ne j, 1 \le i, j \le m$. If any $\hat{r} \in R_{k_i, k_j}$ and $s \in R_{kj, k_i}$ such that $FP_{\hat{r}} \cup FP_{\hat{s}} = F_{k_i}^0 \cup F_{k_j}^0$, then there exists a single swap route for crew k_j to k_i.*

Proof: Since we have $\left(k_i,k_j\right)\in E$, then there is a feasible flight route $\hat{r}$ which contains fights in $F^0_{k_i}\cup F^0_{k_j}$ and it includes in at least one flight in $F^0_{k_j}$. Conversely, since we have $\left(k_j,k_i\right)\in E$, then there is a feasible flight route $\hat{s}$ which contains fights in in $F^0_{k_i}\cup F^0_{k_j}$ and it includes in at least one flight in $F^0_{k_i}$. Since $FP_{\hat{r}}\cup FP_{\hat{s}}=F^0_{k_i}\cup F^0_{k_j}$, we get $F^0_{k_i}\cup F^0_{k_j}\subseteq FP_{\hat{r}}\cup FP_{\hat{s}}$. This fact shows that all fights in $F^0_{k_i}\cup F^0_{k_j}$ can be operated by assigning $\hat{r}$ to k_i and $\hat{s}$ to k_j. So, we found crew swap between crew k_i and k_j.

Proposition 2 states that the existence of cycle $\left\{k_i,k_j,k_i\right\}$does not always guarantee the existence of crew swap between two crews. However, we can use cycle $\left\{k_i,k_j,k_i\right\}$ for identifying candidate crew in swapping process as follows. For $k\in C$, we define $FP^p_k:=\left\{f\in AF \,|\, f\in\mathfrak{R}_k^{AF_k}\right\}$, where AF_k is a set of flights for crew k. Let k^* be a crew who has a delayed flight. Let c_{kp} be the cost for assigning crew k to flight route p. The candidate crew for swapping is determined by

$$CS:=\left\{k\in C \,|\, k\neq k^*, FP^q_k\cap AF_{k^*}\neq\emptyset,\ q\in\mathfrak{R}_k^{AF_k}\right\}. \quad (1)$$

Swapping between crew k and $r\in CS$ can be performed if there exists $p\in\mathfrak{R}_{k^*}^{AF_{k^*}}$ and $q\in\mathfrak{R}_r^{AF_r}$ such that $FP^p_{k^*}\cup FP^q_r=AF_{k^*}\cup AF_r$. If $FP^p_{k^*}\cup FP^q_r=\emptyset$, crew swap will be performed without deadhead. Deadhead will include in swapping if $FP^p_{k^*}\cup FP^q_r\neq\emptyset$, and there is no crew swap if $CS=\emptyset$. Based on this concept, we propose an algorithm for crew swap at Fig. 1.

Algorithm 1 Crew swap procedure

Input: CS, k^*.
Output: Crew t who will swapped by crew k^*.
Initialization: $j\leftarrow 1, b\leftarrow\infty, SW\leftarrow\emptyset$.
while $j\leq|CS|$ **do**
  Find $PS_j=\{(p,q)|p\in P_{k^*}, q\in P_j, FP^p_{k^*}\cup FP^q_r=AF_{k^*}\cup AF_r, FP^p_{k^*}\cap FP^q_r=\emptyset\}$.
  if $PS_j\neq\emptyset$ **then**
    Find $(s,t)\in PS_j$ such that $c_{k^*s}+c_{jt}=\min\{c_{k^*v}+c_{ju}|(u,v)\in PS_j\}$
    if $c_{k^*s}+c_{jt}<b$ **then**
      $SW\leftarrow(s,t), f\leftarrow j$, and $b\leftarrow c_{k^*s}+c_{jt}$.
    end if
    $j\leftarrow j+1$.
  end if
end while
Assign t for crew k^* and s for crew f.

Fig. 1. Algorithm for crew swap.

In crew recovery process, we run the above algorithm firstly. If we do not find a candidate crew for swapping, we will solve a new crew assignment problem. We believe that this procedure will cut down the computational complexity in solving airline crew recovery problem.

4 Computational Results

We tested our algorithm for solving a crew recovery problem of an Indonesia Airline using 300 flights. The flights were included by 52 routes, and those were assigned to 52 crew. We used a number of delay instances where for each case we chose one flight to be delayed, and then we generated the delay duration of the flight randomly. For each delay instance, we identified the candidate crew for swapping. If the candidate crew exist, we run Crew Swap Procedure 1. Otherwise, we solved the optimization model to re-schedule crew assignment proposed by Novianingsih at al. [5]. The model was solved heuristically by executing three procedures, that are CFS Procedure, Improvement Procedure, and Recovery Procedure, sequentially. We used 20 flight delay instances. For each instance, we determined the number of active flights and its possible crew routes that can be constructed using its active flights (see Table 2). According to the data in Table 2, we see that a greater number of active flights will increase the number of possible crew routes.

Table 2. The number of active flights and its possible crew routes for each instance.

Instance	#Active flight	#Possible routes
1	10	35
2	25	129
3	40	198
4	58	257
5	72	301
6	89	380
7	97	466
8	107	576
9	112	687
10	128	850
11	135	986
12	149	1293
13	158	1556
14	166	1701
15	180	1985
16	201	2223
17	220	2440
18	234	2607
19	241	2896
20	250	3014

After active flights was determined, we identified the disrupted crew caused by one flight delay. Then, we determined a set of candidate crew swaps for each disrupted crew. If candidate crews exist, we executed Procedure in Algorithm 1. We record the running time of the procedure in solving the recovery problem, and then we compared it to the running time of Recovery Procedure without swapping in [5]. Table 3 recorded the running time of both procedures.

Table 3. The number of active flights and its possible crew routes for each instance.

Instance	CPU time (minutes)	
	Algorithm 1	Algorithm in [5]
1	0.4	0.9
2	-	1.3
3	0.5	1.5
4	0.6	1.7
5	-	1.9
6	-	2.0
7	0.7	2.4
8	0.7	2.5
9	0.8	2.8
10	1.0	2.9
11	1.0	3.0
12	1.1	3.3
13	1.3	3.6
14	1.4	3.7
15	1.6	3.9
16	1.6	4.3
17	1.7	4.5
18	1.9	4.6
19	2.0	4.9
20	2.1	5.1

According to Table 3, we found that there exist several instances where there is no crew swap, that are Instance 2,5, and 6. For these instances, we only execute Procedure in [5]. For other instances, we obtain that the running time of Algorithm 1 in solving recovery problem is less that the running time of Procedure in [5]. Moreover, a greater number of active flights in recovery problems will result in the longer time to solving the problems. Although crew swaps are not always obtained, we found that the possibility of crew swaps will increase if we have a greater number of possible routes. Based on these results, we conclude that solving crew recovery problem by crew swap is necessary, and it should be performed as the first step of re-scheduling crew.

5 Conclusion

We present proof of concepts on solving airline crew recovery problems by using cycles in crew routes. We identify the existence of crew swap by considering disjoint sets of flights in two crew routes. We propose an algorithm to swap routes between two crew during a flight is delayed. The implementation of our algorithms in solving a number of delay cases shows that our approach works efficiently.

Scheduling in airline recovery includes several resources, it is not only including crew but also aircrafts and passengers. It means that disruption on the operation of crew schedules could affect to disruption on the operation of aircraft schedules or passenger schedules. Therefore, integrating all resources in airline schedule becomes interesting topics, especially on airline recovery problems. We found limited number of research in this area including [15-17].

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