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Operations Research in Crew Scheduling for Airlines

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***Abstract*: Airline Crew Scheduling is an important part of airline operations and an interesting problem for application of operations research. The objective is to assign crew at minimum cost on the basis of given constraints using personalized rosters or bidlines. We have given a far reaching depiction of aircraft crew scheduling issues and numerical models used to solve the different constraints and objectives. We present solution methodologies by integer programming method that has been used to solve crew pairing problem and crew rostering problems.**

***Keywords*: Pairing, Rosters, Operations Research, Binary Variables, Vector**

1. Introduction

"If the Wright brothers were alive today, Wilbur would have to fire Orville to reduce costs." ~ Herb Kelleher

Aviation these days is one of the most booming and important industries as it has drastically increased connectivity and the ease of travelling. It is almost just yesteryear that the science of flight was developed and here we are, in today's age and time, connected to almost every part of the world and constantly specializing in every aspect of modern aviation to increase air travel efficiency. Before we delve into the problems faced by current day aviation, we'll first try to understand what operations management is and how it is implemented in aviation.

The history of aviation extends for more than two thousand years, from the earliest forms of aviation such as kites and attempts at tower jumping to supersonic and hypersonic flight by powered, heavier than air jets. As civil aviation gained more and more popularity in the late 20th century and air passengers traffic started picking up drastically, the aviation industry started facing a lot of challenges which were unprecedented. Operations Management emerged as the central strategy for the survival of this industry.

Now, Operations management is the administration of business practices to create the highest level of efficiency possible within an organization. It is concerned with converting materials and labour into goods and services as efficiently as possible to maximize the profit of an organization. Operations management teams attempt to balance costs with revenue to achieve the highest net operating profit possible. Operations Management has always been an integral part of the airlines industry. Both go hand in hand.

The aviation industry has always been plagued by high debts and poor ability to service the same with revenues. Since time immemorial, Airlines have witnessed nosediving debts and a strong struggle to barely keep the company afloat. These majorly owe to the components which comprise its cost structure- Fuel cost, lease and rentals, maintenance, HR and Administration, etc. The most important and the most uncertain cost is that of Fuel. The prices of Aviation turbine fuel fluctuate as a result of the economic environment and not much could be done to regulate them. In the 1990s, the aviation industry saw some of its worst years and thereby emerged the phenomenon of Low-Cost Carriers (LCCs). This meant that airlines were ready to offer tickets at extremely low prices to increase passengers and thereby marginally increase revenues. This also meant that the airlines had to reduce their costs drastically in order to stay profitable. Herein came advanced applications of Operations Research. Operations Management helped in various ways. Airlines were already using Operations to optimize their flight routes but the emergence of LCCs gave a new twist to it. From timing aircrafts strategically and deciding their routes in order to optimize operations, reduce costs and prevent accidents, Operations was also applied in scheduling crews. On the implementation of efficient Operations practices, costs saw a drastic reduction as aircrafts now travelled on the shortest routes thereby reducing fuel costs, waited for the minimum time at airports thus reducing airport charges and increasing aircraft utility and crew was assigned in a way that there was no excess manpower employed.

This research paper focuses on the specific issue of application of Operations Management in Crew Scheduling in Civil Aviation with an aim to provide literature to develop techniques which will reduce costs related to it, simultaneously ensuring increased human resources efficiency.

2. Overview of the Industry

During the 100 years since the first flight of Orville and Wilbur Wright, the air transport industry has grown into a major sector of the global economy. Even more importantly, it has become essential to developing and maintaining cultural and economic links among countries and people. According to IATA, passenger numbers could double to 8.2 billion in 2037. Over the next two decades, the forecast anticipates a 3.5% compound annual growth rate (CAGR), leading to a doubling in passenger numbers from today's levels. This means that airlines in the future would face the need to be more competent and efficient. This again brings us back to how airlines need to up their operations management in order to be able to make the best out of this opportunity and serve their customers better.

After spending roughly its first 40 years trying to get off the ground, literally at times, the air transportation industry grew by leaps and bounds in the latter 60 years. Throughout the second period, Operations research has played a critical role in helping the airlines industry and its infrastructure sustain high growth rates and make the transition from a novelty that catered to an elite clientele to a service industry for the masses. Operations Research has since been extensively used in the classical problems of scheduling, routing and crew assignment. It mainly used large scale, discrete optimization approaches and indeed, has motivated several methodological and computational developments in the vibrant area of Operations Research. More recently, OR has been used in Airline revenue management, including overbooking, flight leg yield management and network revenue maximization. Through a combination of stochastic and optimization models, OR work in this area has generated significant additional revenue for the airlines. OR techniques have also been used in Airport Systems and Air Traffic Management Systems. This field makes uses of both deterministic and stochastic models.

In this research paper, we will specifically be dealing with application of OR in Crew Scheduling problems. Therefore, it becomes important to have a concrete overview of the developments in this particular area. Now because of the immense size of the airline crew scheduling problems, i.e., thousands of constraints and billions of variables, researchers initially depended on heuristic methods to achieve solutions. Heuristics however had a huge drawback which was that the quality of the solutions could not be quantified with relation to an optimal solution. This led to development of more advanced and efficient methods like the Branch and Price method. We will be discussing one such method of solving Crew Scheduling problems ahead.

3. Research Objectives

- To understand the importance of cost-efficient crew planning.
- To find solutions while maximizing profits and minimising costs.
- To elaborate our understanding regarding the complexity of crew rostering.
- To outline the various constraints faced by airline industry with respect to their crew.
- To describe briefly, the crew pairing problems along with their concepts, models and algorithms

4. Research methodology

The research methodology used is secondary data. This research paper selects, analyses and consolidates information from various other research papers which had findings related to the Application of Operations Research in the Airline Industry.

A vast set of secondary data from various authors was collected and organised to make this research paper.

For the collection of secondary data we have used both published and unpublished data. Published data are collected from: i) various publications of journals and other research papers ii) various research reports are prepared by research scholars, universities, economists, etc., in different fields, iii) books of various authors, magazines, and newspapers, iv) various sources from university libraries, v) technical and trade journals, vi) websites, and vii) public records and statistics, historical documents and other sources of published information.

The unpublished data are collected from many sources. They are found in diaries, letters, unpublished biographies and autobiographies, and also from scholars and research workers, trade associations,

We have studied research works of various scholars in details during our research works. We have tried our best to present every chapter in some detailed mathematical techniques with some new concepts. The analysis was undertaken to develop the skill of Application of Organisation Research in the Airline Industry. In addition, this thesis includes solutions using methodologies such as integer programming to name a few.

5. Literature Review

This paper gave a description of real-world airline crew rostering problems and the mathematical models used to capture the various constraints and objectives found in the airline industry.

The model used initially was the mathematical model, they initially introduced a simplified model of the problem and then increased it subsequently. They first assigned 2 variables – one containing assignable activities (such as ground duties and reserves) and the second containing crew members. The second step they formed a linear equation with attempts to minimize the cost of each variable with the help of vectors.

They also mentioned the three main components of the automatic planning functionality of the Carmen Crew Rostering system: the rule evaluator, the generator and the optimizer. The purpose of the generator is to generate a large number of possible rosters for each crewmember. The optimizer chooses one roster per crewmember while ensuring that all pairings and other duties are assigned and various constraints are respected. The generator uses the rule and value evaluator to ensure legality of the rosters generated and to calculate the other attributes of the generated rosters.

The limitations are that this model is computerized and can lead to wrong outputs if any variable is assigned incorrectly (NIKLAS KOHL, 2004)

They used a system called the Air Crew Scheduler which is an interactive computer software system for air crew scheduling. The system is used by planners to develop and modify crew pairings for flight crews and cabin crews.

The input variables are flight leg (which is the flight between 2 cities, departing and arriving at specified times) and a duty period. The pairing pattern is a sequence of duty periods that a crew member must complete keeping in mind the rest periods required (which changes for long haul and short haul flight) and minimization of cost

The limitations are that most of these models are computer based which means that they are not 100% efficient. Not only this buy also if one variable is allotted wrongly, it will lead to an extra cost that otherwise could have been avoided. (University, 1997)

There are immense airline crew scheduling problems having thousands of constraints and billions of variables and to solve this issue, researchers initially focused on having an approach which led to problem solving, learning, or discovery that employs a practical method not guaranteed to be optimal or perfect, but sufficient for the immediate goals. Such an approach had few drawbacks like the quality of their solutions could not be computed relative to the optimal solution. To get a solution which is close to the optimality, researchers turned to the branch-and-price model. It is a complex technique in which column generation is used, through which extensive linear programs can be solved without manually adding variables or columns, one by one. It directly solves the restricted master problem which is the subset of the predominant column rather than solving the entire problem. The dual solution to the restricted master problem is used to find out columns with negative reduced cost. The column is the added to the restricted master problem and then resolved until no negative reduced cost columns are present. In this crew pairing problem, negative reduced cost columns are found without considering each pairing, whereas columns are found by solving a pricing problem. Branch-and-price algorithms is difficult to implement if there are contrasting variables. Instead, a branch-on-follow-on branching rule is typically used, this method states that one flight should immediately follow the other. To improve on this, researchers use the variable-fixing approach in which variable values having decimal close to one have been rounded off which leads to improving the optimality. When you combine subsets of columns with an optimization-based pricing approach it leads to improved solutions. (Barnhart, 2003)

6. Problem Description

After costs for fuel, crew costs constitute the second largest expenses of an airline. Since profit is the difference between revenue and cost, cost efficient crew planning is of major importance for airlines. The input for a crew rostering problem consists in general of crew information, activities to be rostered, rules and regulations, and objectives for the creation of the rosters.

When producing personalized rosters, each crewmember's personal records (such as hours flown, equipment the crew member can operate or a destinations the crew member cannot fly to), qualifications, pre-assigned activities, and vacation days are given; languages spoken by the crew members are important during international flights.

Following is a list of certain constraints that should be taken into consideration while crew scheduling

- Person, time and task compatibility
- Rest time required by each member between the tasks
- Crew complement (this is in reference to long haul or short haul flight)
- Qualification constraints
- Number of Inexperienced crew members on one flight should be limited
- In many cases, certain crew members must be assigned together
- In some cases, crew members may be incompatible with each other
- Language qualifications

7. Solution

On any flight leg there is a requirement for a given number of crew of different categories. A flight is completely covered only when all of its basic crew resource requirements are met with sufficiently with qualified crew members. Crew in one category cannot substitute crew in other category and different rules apply to each category so crew scheduling problem decomposes by crew category. Crew in airlines is typically partitioned into two categories: Cabin Crew and Cockpit Crew. Cabin crews includes the flight attendants that are responsible for the comfort and safety of the passengers, and cockpit crews includes the pilots that are responsible for operation of the aircraft and execution of the flight leg. Most optimization research on airline crew scheduling has focused on the pilot problem, primarily because cockpit crews are paid substantially more than cabin crews. The cockpit crew problem is also smaller and simpler in structure than the cabin crew problem, for reasons including:

- Cockpit crews, unlike cabin crews, stay together throughout the workday, allowing crews, instead of individuals, to be modelled.
- For each flight leg, the size and composition of the cockpit crew is known a priori, based upon the defined requirements for each aircraft. The cabin crew size, however, varies as a function of the number of passengers on the flight leg.
- Cockpit crews have fewer options: They can be assigned only to those flight legs with assigned aircraft types that they are qualified to fly. Cabin crews have much more flexibility, with only limited restrictions on the type of aircraft to which they are assigned. (Amy Cohn, 2004).

For both cockpit and cabin crews, the crew scheduling problem itself is usually solved differently. It is typically broken into two sequentially solved subproblems. First, a set of minimum-cost work schedules (pairings) is determined. The second step in solving crew-scheduling problems is to assemble pairings into monthly work schedules, called rosters, and assigning them to individual crew members. So, the crew scheduling problem can be broadly classified into two steps: Crew Pairing Problem and Crew Rostering Problem.

8. Crew Pairing Problem

The pairing problem deals with the construction of itineraries consisting of flights such that all flights of a given schedule are completely covered. Here, minimum-cost, multiple-day schedules called pairings are generated. Pairings is a sequence of flight legs for unspecified crew members that should be starting and ending at the same crew base. The crew members will usually be working on these legs, but a pairing may also contain deadheads, where the crew members is not working but is just transported as a passenger. Regulatory agencies and collective bargaining agreements specify the many work rules that define how flight legs can be combined to create feasible schedules. Work-rule restrictions include limits on the maximum number of hours worked in a day, the minimum number of hours of rest between work periods, and the maximum time the crew may be away from their home base. Pairings must satisfy a large number of government regulations and collective bargaining agreements, which vary from airline to airline. The rules dictate connections between flights (e.g., minimum connection time), possible duties, possible night stops, minimum rest time, and possible combinations of duties depending on total flight/duty time. (Claude P. Medard, 2007). Feasible pairings must start and end at the same crew base. For each duty period that does not end back at the base, there will be the intervening crew rest period, or "overnight", which consists of the start and end times of the rest period, its duration, and in practice a specified hotel where the crew will stay. Even with these limitations, the number of feasible pairings measures in the billions for major U.S. airlines. The cost structure of pairings adds further complexity, with cost typically represented as a nonlinear function of flying time, total elapsed work time, and total time away from base. (Barnhart, 2003). The pairing process considers all tangible costs associated with the operation of a given flight schedule. The main objective in this step is to use the minimum number of crew members to cover the complete flight leg requirements and thus minimise the cost of crew.

In order to make sets of feasible pairings, a crew-need vector of the kind [A1/A2/A3/A4//B1/B2/B3/B4...] can be used to model a basic flight requirement. Let A be the cockpit crew and B be the cabin crew. Here // stands for separating the main categories of cockpit and cabin, and a single / stands for separating the number of crew that is required within each of the sub-categories. Suppose if the cockpit crew consists of Captain, First Officer, Flight Engineer and Navigator and cabin crew consists of Flight Attendants, Pursers, Flight Medic and Loadmaster, the crew-need vector can be written as [1/1/2/0//2/2/1/0] which denotes that one captain, one first officer, 2 flight engineers and no navigator are needed in cockpit, and 2 flight attendants, 2 pursers, one flight medic and no loadmasters are needed in cabin. For both cockpit and cabin crews, the crew-scheduling problem has to be solved sequentially because of the reasons discussed. So one approach in decomposition of this problem could be slicing flight's original crew-need vector into the cockpit and cabin. Slicing can be done as [1/1/2/0//0/0/0/0] for the cockpit crew requirement and [0/0/0/0//2/2/1/0] for the cabin crew requirement. All flights in the schedule are then grouped in the slice categories that add up to their original crew-need. There could be instances where there are some fleets with cabin crew requirement of [0/0/0/0//2/2/1/0] while others with [0/0/0/0//2/4/1/0]. In this case, slicing can be done in accordance to the greatest common need: all [0/0/0/0//2/4/1/0] flights are first planned together with the [0/0/0/0//2/2/1/0] flights in that slice, and then planned in [0/0/0/0//0/ 2/0/0] slice to cover the extra need in one slot.

9. Modelling

The required crew pairing problem can now be modelled as an Integer program. The optimisation problem is formulated under the assumption that the set of possible pairings and their costs are explicitly available. The problem has one binary decision variable, x_p, $_p \in P$, for each possible pairing denoting whether the pairing is used or not. It is one if the pairing is used and zero otherwise. Here, *S* is the set of all slices and P is the set of possible pairings. Integer program can be formulated as following:

$$\text{Min:} \quad \sum_{p\in P} C_p X_p$$
$$\text{Subject to:} \quad \sum_{p\in P} a_{ip} x_p \geq n_i \quad \forall i \in I(s)\,, \ \forall s \in S \qquad (1)$$
$$\sum_{p\in P} b_{jp} x_p \leq m_j \quad \forall j \in J \qquad (2)$$
$$x_p \in \{0,1\} \ \ \forall p \in P \qquad \text{(Claude P. Medard, 2007)}$$

C_p denotes all the tangible costs incurred for the crew including hotels in case of overnight stays. *I(s)* denotes the set of flights to cover in slice *s*, and a_{ip} is a binary coefficient that is one if pairing *p* covers flight *i* and zero otherwise. For constraint (1) *ni* is the number of times flight *i* must be covered in that slice, for example for slice [0/0/0/0// 2/2/1/0] *ni* = 1. It expresses that each leg must be covered exactly the desired number of times. Constraint (2) is a set of global constraints that applies to a group of pairings altogether. In this case, b_{iP} could be the work load for pairing *p* if it starts and ends in base *j*, 0 otherwise; m_j is the maximum workload allowed for base *j*. Set *J* denotes the set of all constraint types which limit some property of a set of pairings.

Here, the objective of this integer program is to minimise the cost of crew while considering constraints like allocating only the required number of personnel, overworking of members etc.

10. Crew Rostering Problem

In addition to the complexity already described, crew-scheduling models must also incorporate a host of other constraints, including crew-base requirements, work balance concerns, etc. Moreover, depending on whether the flight schedule is domestic or international, different modelling and solution techniques are required. (Barnhart, 2003). Crew Rostering Problem combines the pairings from above problem into equitable and efficient month-long crew schedules, called rosters, assigning them to individual crew members. In crew rostering, the pairings together with possible other activities such as ground duties, reserve duties and off-duty blocks are sequenced to rosters. With rostering, schedules are constructed for and assigned to specific individuals, taking into consideration their particular needs or requests. Rostering is usually done one month at a time and each roster usually has some history.

In contrast to pairing, crew rostering can be done in various ways following different approaches. In North America for instance, at most airlines the rostering is done in two steps: first, anonymous rosters (or so-called "bidlines") are created which are then assigned to individuals based on bids for these anonymous rosters. We refer to this rostering approach as the bidlines approach. At most European airlines, however, individual rosters are constructed directly for each crewmember, which we refer to as personalized rostering. This approach can be based on fair share, i.e., all crewmembers should have rosters satisfying certain quality criteria, or on individual preferences. In the latter case, crew members express personal preferences that are considered during the creation of the individual rosters. These preferences can be awarded according to seniority, i.e., the most senior crewmembers get a maximum of their preferences granted limiting the awards of less senior crewmembers, or again on a fair share basis. When producing rosters, each crewmember's personal records, qualifications, pre-assigned activities, and vacation days are given. The records usually contain accumulated attributes such as hours flown during the current calendar year. Other values of interest are due dates for training or possible exceptions from certain rules and regulations. Personal qualifications contain for instance information about the equipment the crewmember can operate or a list of destinations the crewmember cannot fly to. For cabin crew, language proficiency is an important qualification for international flights. Pre-assigned activities could be training, office duties or medical checks (NIKLAS KOHL, 2004).

The goal is to minimize costs while considering quality of life criteria and taking into account the rostering rules that need to be followed while planning. Some examples of these rules are rules limiting the number of hours the crew is allowed to work in a specified period of time. Some of these might be applied on a rolling basis from week to week or month to month. We also need to consider rules ensuring that the crew is qualified for the assigned pairing. These rules typically depend on the aircraft, airport of the pairing and the language, visas requirements for the crew.

11. Modelling

Denote by C the set of crew. Let R_C be the set of feasible rosters for crew member $c\in C$, x_{cr} a binary decision variable denoting whether roster r is chosen for crew member c, A the set of all activities to plan for (pairings and other), K the set of categories to plan (e.g., in cockpit: captain, first officer, and maybe an extra position for a trainee), Q the set of pairings or flights for which an additional qualification constraint must hold. u_{acr} is a binary coefficient taking value 1 if activity a is covered by roster r for crew c, n_{ak} is the number of crew needed for activity a in category k. The optimization problem which needs to be solved is given by:

Min: $\sum_{c\in C, r\epsilon R_c} f_{cr} x_{cr}$

Subject to: $\sum_{r\epsilon R_c} x_{cr} = 1 \quad \forall c \in C$ (1)

$\sum_{c\in C, r\epsilon R_c} u_{acr} x_{cr} = 1; \quad \forall a \in A; \quad \forall k \in K$ (2)

$\sum_{c\in C, r\epsilon R_c} v_{acr} x_{cr} \leq b_{aq;} \quad \forall q \in Q; \quad \forall a \in q(A) \subseteq A$ (3)

$x_{cr} \in \{0,1\}; \quad \forall r \in Rc; \quad c\in C$ (Claude P. Medard, 2007)

f_{cr} denotes the cost of roster r for crew c. Constraint (1) ensures only one roster per crew is selected. Constraint (2) ensures each planned activity is covered for each crew category. Constraint (3) models the multi-roster constraints, where Q represents the set of constraints which need to be satisfied by the complete solution; $q(A)$ is the set of activities which have the additional constraint q. The coefficient v_{aqcr} is the contribution of roster r for crew c with respect to qualification q and activity a, and b_{aq} is the limit imposed by the constraint q on rosters covering activity a. Examples of constraints of type (3) are 'at most one inexperienced crew member must fly on this trip', 'such crew members must not fly together', 'this trainee must fly with his instructor', and 'at least one crew member must speak a certain language'.

In this integer problem we aim at minimising the cost of rostering while considering constraints like covering of all required activity in the required category.

12. Findings and Conclusion

With crew cost being the second highest cost for the airline industry, it becomes important to try to minimise the cost to attain the following managerial benefits.

- Help drive efficiency, reduce crew costs and improve utilization, while producing resilient crew schedules that withstand day-of-ops changes.
- Provide a unified, integrated platform with a wide range of capabilities for easier interoperability across the crew environment and simplified technology management.
- Offer simplified crew administration with a wide range of integrated functions.
- Provide advanced interfaces and decision-support tools such

as alert-based management that helps improve crew-management productivity and performance while reducing costs.

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