HYBRID METHODS FOR INTEGRATED AIRCRAFT ROUTING AND CREW PAIRING PROBLEM WITH SHORT FLIGHT LEGS

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UNIVERSITI TEKNOLOGI MALAYSIA
HYBRID METHODS FOR INTEGRATED AIRCRAFT ROUTING AND CREW PAIRING PROBLEM WITH SHORT FLIGHT LEGS

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A thesis submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy (Mathematics)

Faculty of Science
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To my late father, mother, husband and family for their never ending support and care
Praise to Allah, The Most Gracious and The Most Merciful Lord for His Blessing. This thesis is the end of my long journey in completing my PhD research. During this journey, I have met many individuals and friends and gained valuable knowledge. I would like to express my sincere gratitude to all contributions that have been essential for the completion of this thesis.

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ABSTRACT

The aircraft routing and crew pairing problems are two processes that are difficult to be solved in the airline operations planning due to the rules that each flight leg needs to be operated on by one aircraft and one crew pair. These two problems, though interrelated in practice, are usually solved sequentially and often leads to suboptimal solution. Thus, this research contributes to the solution of the integrated aircraft routing and crew pairing problem in order to determine the minimum cost of this integrated problem where each flight leg is covered by one aircraft and one crew pair. This study also considers short connection between two flight legs in order to ensure that the crews do not change the aircraft if the connection time is in between 20 to 59 minutes. Another consideration is the restricted connection that imposes penalty costs when the second flight leg uses the same crew but not the same aircraft. Based on the literature review, most of the existing solutions concentrate on minimizing the planned costs. Although the minimum costs are significantly important in airline operations planning, the efficiency of a solution method in terms of computational time cannot be neglected. It is necessary to solve the integrated problem by using an efficient model that is able to generate a good high quality solution in a short time as requested by the airline industry. In order to solve the problem, a set of feasible aircraft routes and crew pairs are initially generated to be used as the input data in solving the integrated model effectively. There are two heuristic methods which are proposed in generating the set of feasible aircraft routes and crew pairs namely constructive-based heuristic and Genetic Algorithm (GA). The generated feasible aircraft routes and crew pairs are then used in solving the integrated problem by using Integer Linear Programming (ILP) method, Dantzig Wolfe Decomposition method, Benders Decomposition method and Particle Swarm. Computational results obtained from these methods are then compared by testing them on four types of aircraft with different number of flight legs based on Malaysia local flights for one week flight cycle. From the numerical results, it can be concluded that the proposed methods are more efficient compared to the ILP method available in the literature in terms of the computational time where the hybrid algorithm of GA and Benders Decomposition is found to be advantageous compared to the others. The maximum cost deviation of only 4.77% also justifies the strength of this hybrid algorithm. One possible future research that can be extended from this study would be the development of an algorithm that incorporates a parallel GA within the proposed methods for larger instances which are likely to exist in international flights in order to speed up the planning process.
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<td>Air Transport Action Group</td>
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<tr>
<td>IATA</td>
<td>International Air Transport Association</td>
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<tr>
<td>NP</td>
<td>Non-deterministic polynomial-time</td>
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<td>ILP</td>
<td>Integer linear programming</td>
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<tr>
<td>MILP</td>
<td>Mixed integer linear programming</td>
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<tr>
<td>RMP</td>
<td>Restricted master problem</td>
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<td>LP</td>
<td>Linear programming</td>
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<td>GA</td>
<td>Genetic algorithm</td>
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<td>Flying time</td>
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<td>Pressure cycles</td>
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<td>Ringgit Malaysia</td>
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LIST OF SYMBOLS

\( M \) - Set of maintenance stations
\( B \) - Set of crew bases
\( R \) - Set of two flight legs that has a restricted connection
\( S \) - Set of two flight legs that has a short connection
\( F \) - Set of flight legs in the schedule
\( p_{m}^{A} \) - The source nodes for aircraft routes
\( q_{m}^{A} \) - The sink nodes for aircraft routes
\( p_{b}^{C} \) - The source nodes for crew pairs
\( q_{b}^{C} \) - The sink nodes for crew pairs
\( \alpha^{m} \) - Set of feasible aircraft routes from the source node \( p_{m}^{A} \) to a sink node \( q_{m}^{A} \) in \( N_{m}^{A} \)
\( \alpha^{b} \) - Set of feasible crew pairs from the source node \( p_{b}^{C} \) to a sink node in \( N_{b}^{A} \)
\( w_{\mu m}^{f} \) - Equal to 1 if leg \( f \) belongs to aircraft route \( \mu \in \alpha^{m} \), and 0 otherwise
\( w_{\varphi b}^{f} \) - Equal to 1 if leg \( f \) belongs to crew pair \( \varphi \in \alpha^{b} \), and 0 otherwise
\( c_{\mu m} \) - The cost of using the aircraft route \( \mu \in \alpha^{m} \)
\( c_{\varphi b} \) - The cost of using the crew pair \( \varphi \in \alpha^{b} \)
\( n_{\mu m}^{ij} \) - Equal to 1 if legs \( f_{i} \) and \( f_{j} \) are operated sequentially in aircraft route \( \mu \in \alpha^{m} \), and 0 otherwise
\( n_{\varphi b}^{ij} \) - Equal to 1 if legs \( f_{i} \) and \( f_{j} \) are operated sequentially in crew pair \( \varphi \in \alpha^{b} \), and 0 otherwise
\( l_{\mu} \) - The number of required aircrafts in the aircraft route \( \mu \in \alpha^{m} \)
\( \omega^A \) - The number of available aircrafts

\( \omega^B \) - The number of duty periods allowed in a crew pair

\( \omega^C \) - The number of short connections allowed in one aircraft route

\( \nu_\varphi \) - The number of duties in crew pair \( \varphi \in \alpha^b \)

\( s_\mu \) - The number of short connections in aircraft route \( \mu \in \alpha^m \)

\( z_{ij} \) - Penalty cost associated with \( (f_i, f_j) \in R \)

\( \xi_\mu \) - Binary variable that represents the flow on the aircraft route \( \mu \in \alpha^m \)

\( \eta_\varphi \) - Binary variable that represents the flow on the crew pair \( \varphi \in \alpha^b \)

\( P_{ij} \) - Binary variable that represents the penalty costs for \( (f_i, f_j) \in R \)

\( \beta \) - Dual variable of dual sub-problem of Benders decomposition method

\( \gamma \) - Dual variable of dual sub-problem of Benders decomposition method

\( \delta \) - Dual variable of dual sub-problem of Benders decomposition method

\( \vartheta \) - Dual variable of dual sub-problem of Benders decomposition method

\( \chi \) - Dual variable of dual sub-problem of Benders decomposition method

\( y_0 \) - An additional free variable of Benders decomposition method

\( P_\Lambda \) - Set of extreme points

\( R_\Lambda \) - Set of extreme rays

\( \Delta \) - Polyhedron

\( \rho \) - Iteration number of the solution

\( V_\varphi \) - Matrix for all variables \( \eta_\varphi \)

\( V_\mu \) - Matrix for all variables \( \xi_\mu \)

\( \delta^A \) - Vector for constraint (5.37)

\( \delta^P \) - Vector for constraint (5.38)

\( N \) - Number of population in particle swarm optimization

\( D \) - Dimension of the problem in particle swarm optimization

\( f \) - Fitness function in particle swarm optimization

\( v \) - Velocity in particle swarm optimization

\( r \) - Random number

\( x_{gb} \) - Global best solution

\( x_{lb} \) - Local best solution
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<tr>
<td>$u'$</td>
<td>Extreme ray</td>
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<tr>
<td>$u^0$</td>
<td>Extreme point</td>
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<tr>
<td>$\epsilon$</td>
<td>Arbitrary tolerance</td>
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<tr>
<td>$\mathbb{Z}$</td>
<td>Integer numbers set</td>
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CHAPTER 1

INTRODUCTION

1.1 Overview of the Problem

In this chapter, we first provide an overview of the airline operations planning. One of the first industries that apply operation research methods to solve optimization problem is the airline industry (Snowdon and Paleologo, 2009). For nearly five decades, air transport has given public benefits. According to the Air Transport Action Group (ATAG), it seems that 40% of tourists use air transport and roughly, two million passengers use aviation transport annually. While according to International Air Transport Association (IATA), the profits obtained in the industry has been twice over the past decade from US$369 billion in 2004 to $717 billion in 2016. Nowadays, the airline industry has more than 2000 airlines that operate more than 23,000 aircrafts for over 3700 airports (IATA).

Even though the airline industry has been expanding, the patterns of development in the airline industry are still disappointing. The consumers’ satisfactions are hard to fulfill due to the challenge in improving the aircraft service. Since the improvement of the aircraft is absolutely expensive, the payback is a long way in achieving. Besides that, the other problem faced by the airlines all over the
world is to improve operational efficiency while the costs are being reduced. Thus, in
order to overcome the margin’s problem by the airlines, they need to take a good
care of the customers’ preferences by offering good opportunities and gradually
develop the technology involved in the development of airlines industry.

As airlines manage hundreds of aircrafts and hire thousands of workers, they
encounter complicated decision making processes along the planning procedure. The
planning procedure cannot be made concurrently due to the higher number of airlines
planning process involved. Traditionally in airlines, a sequential approach is used in
the planning step. There are four processes in the airline operations planning namely
the schedule design, fleet assignment, aircraft routing and crew scheduling that
consists of crew pairing and crew rostering. Each process in the airline operations
planning involves many decisions that may affect the other decisions. Because of the
sequential approach in the airline operations planning, not all the solutions obtained
are optimal. Sometimes, the previous process attains optimal solutions, and then by
using those solutions in the next process, the newly obtained solutions are no longer
optimal. For example, there is no information about aircraft availability in solving
fleet assignment problem which means the fleet assignment does not consider the
unavailability of aircraft due to maintenance checks. Consequently, the number of
available aircraft in covering all flights may be insufficient for certain aircraft types.
Besides that, the costs will be increased when the interdependence between processes
in airline planning process is conducted.

The remaining part of the chapter is dedicated to the explanations of the
background of problem, problem statement, research questions, objective of study,
scope of study, significance of study and lastly organization of thesis.
1.2 Background of Problem

Among the four processes in the airline operation planning, aircraft routing and crew pairing problem are the most important processes in the airlines. The aircraft routing problem determines the routes so that all the scheduled flights are covered by an aircraft and to ensure that the maintenance of the aircrafts are done. The crew pairing problem is one of the processes that involved high costs in the airline planning. Some of the latest works on aircraft routing problem are Lan et al. (2006), Sarac et al. (2006), Haouari et al. (2009), Lacasse-Guay et al. (2010), Liang et al. (2011), Lapp and Cohn (2012) and Basdere and Bilge (2014). Some details of crew pairing problem were established in some of the past works of Souai and Teghem (2009), Saddoune et al. (2010), Deng and Lin (2011), Saddoune et al. (2011), Duck et al. (2011), Ionescu and Kliewer (2011), Azadeh et al. (2013), Saddoune et al. (2013), Aydemir-Karadag et al. (2013), Muter et al. (2013). Aircraft routing and crew pairing are usually solved sequentially in practice. The sequential process in solving aircraft routing and crew pairing problems leads to suboptimal solutions. The integrated model of aircraft routing and crew pairing problems will need to be solved in order to get an efficient solution.

The background study leading to the research problem can be summarized in Figure 1.1.
**Motivation**
- The maintenance requirements in aircraft routing problem are important as they are commanded by manufacturers and aviation authorities.
- In the crew pairing problem, crew cost is the second higher costs involved in airlines system after fuels’ costs.
- Aircraft routing and crew pairing are usually solved sequentially in practice leading to suboptimal solutions. The integrated model of aircraft routing and crew pairing problems will need to be considered in order to get the efficient solution.

**Existing work: solution methods**
- Sequential approach and plane count constraints.
- Benders decomposition with column generation.
- Iterative method.

**Scenario**
- The integrated model has large number of constraints (Mercier et al., 2005).
- No computationally efficient method was proposed for this problem with encouraging solution (Mercier and Soumis, 2007).

**Limitation**
- Hard to solve the integrated model with large number of constraints.
- The exact method takes longer times in solving the problem.
- The heuristic method does not give an optimal solution.

**Desired Solution**
- We need solution method to solve the integrated model of aircraft routing and crew pairing problems that balance the quality of solution obtained and the time required to compute a solution.

*Figure 1.1* Scenario leading to the statement of the problem
1.3 Problem Statement

With higher demands of air transportation, the airlines have established a refined airline operation planning. The airline operation planning consists of four processes. Therefore, the integration between those processes is very important to assure that the airlines provide good service to their customers. Obviously, the integration between the processes in airline operation planning is very complicated. Clearly the bottleneck in this problem is the complicated mathematical modelling and the methods used which makes the computational times involved are expensive.

There are several works that have been done on the integrated models in the airline planning process to avoid high costs and inefficient solutions involved when the processes are being solved individually. Most of the integrated models from past researches focused on minimizing the planned costs. The first research that integrates aircraft routing and crew pairing problems was by Cordeau et al. (2001). Though the authors established a useful integrated model, but their approach could only solve the medium size instance within a reasonable computational time.

Klabjan et al. (2002) solved integrated aircraft routing and crew pairing problems sequentially and also adds plane count constraints. The authors assumed that the maintenance checks need to be done during the night. This assumption cannot be used for the international flights because the maintenance checks for the aircrafts in the international procedure do not take place at night. Cohn and Barnhart (2003) also demonstrated integrated model but they used the variables with the complete solutions of aircraft routing. Although the number of constraints were decreased, but this approach led to an immense number of variables in the integrated model.

Mercier et al. (2005) introduced the concept of restricted connection in their work. The authors used Benders decomposition method in solving the integrated
model of aircraft routing and crew pairing problems. The crew pairing problem was used as the Benders master problem while the aircraft routing problems was used as the subproblem. This research used high computational time in generating the results of integrated model. Weide et al. (2010) proposed an iterative approach in solving the integrated model of aircraft routing and crew pairing problems. The obtained results were compared with the solutions by Benders decomposition method. The iterative approach is not encouraging enough compared to Benders decomposition method in term of computational time. Besides that, Duck et al. (2011) and Dunbar et al. (2012) also proposed the iterative approach in solving the integrated model of aircraft routing and crew pairing problems. Although both works computed acceptable solutions for the problems, but they were time consuming.

The main aim of this research is to develop an efficient method in term of solution quality and solution time involved for solving the integrated model of aircraft routing and crew pairing problems with the use of mathematical programming model and methods. In finding the balance between the quality of solution and the computational time, heuristic approach is also considered.

1.4 Research Questions

The problem statement raises several research challenges. These challenges will be addressed by providing answers to the following questions:

i) Understanding the rules and criteria in generating the feasible aircraft routes and crew pairs.
   a) What are the rules that need to be satisfied in generating feasible aircraft routes and crew pairs?
   b) What are the methods that can be used for producing feasible aircraft routes and crew pairs?
ii) Reviewing and evaluating existing mathematical model of integrated aircraft routing and crew pairing problems.
   a) What parameters and variables involved in the integrated model?

iii) Determining appropriate key modelling concept for the aircraft routing and crew pairing problems.
   a) What is the approach to be adopted in building this model?
   b) What are the parameters and variables involved?
   c) What are the assumptions that need to be made?
   d) What are the constraints involve?

iv) Building the model.
   a) How to formulate the problem mathematically using all the information from the previous stage?

v) Computation of solution.
   a) What is the best method to use in finding the solution to the developed model of aircraft routing and crew pairing problems?
   b) What parameter should be considered in evaluating the performance of the proposed approaches?

1.5 **Research Objectives**

The objectives of the study are as follows:

i) To develop the methodologies for producing the feasible aircraft routes and crew pairs.

ii) To develop the methodologies for finding the best aircraft routes and crew pairs.

iii) To analyze the performance of the proposed methods under various parameters’ values and problem sizes.
1.6 Scope of the Research

In the sequential approach of airline operations planning, suboptimal solutions occurred in some cases. Due to this, this research will consider the integrated model of the aircraft routing and crew pairing problem. The exact and heuristic methods are used in solving the integrated model. Under the assumption that the maintenance check is to be done at night which means that all the aircraft are on the ground since this research work only focuses on the domestic flights. This is to ensure that the feasible solutions of aircraft routing problem are generated. The flight legs that involved in this problem are specific in Malaysia only. In addition, the short and restricted connections are included in the integrated model. The constraint of short connection is used to ensure that the crews do not change the aircraft when the connection between two associated flight legs is said to be short that is 20 to 59 minutes. Additionally, the constraint of restricted connection is to increase the robustness of airlines as a penalty cost is imposed when crews change the aircraft for two associated flight legs between 60 to 90 minutes.

1.7 Significance of the Research

This study focuses on developing the methods for solving the integrated model of the aircraft routing and crew pairing problems. The importance of this research can be seen in both advancement of knowledge and also its practical contribution to the real life world. The main contributions of this study are summarized as follows:

i. Development of exact and heuristic method for solving integrated model of aircraft routing and crew pairing problems.

ii. Analyzation of the performance of the proposed exact and heuristic method in terms of costs and computational time for various parameter values and problem sizes.
iii. As a reference for solving real integrated model of aircraft routing and crew pairing problems in airlines.

1.8 Organisation of Thesis

The thesis is organized into seven chapters. The organization of the thesis is as follows:

Chapter 1: Introduction
This chapter provides the overview of airlines planning operations that consists of four processes which are schedule design, fleet assignment, aircraft routing and crew scheduling which are divided into two parts, crew pairing and crew rostering. Besides that, it also includes the discussions on the overview of the problem, background of problem, problem statement, research questions, research objectives, scope of the research and significance of the research.

Chapter 2: Literature Review
This chapter provides a comprehensive literature review of the research areas. The research areas involved are the aircraft routing problem, crew pairing problem and the integrated aircraft routing and crew pairing problems. The discussion on the current scenario and research gap are also given. These informations are useful in determining the research direction.

Chapter 3: Research Methodology
In this chapter, the research design and procedure are provided for a better understanding of the steps taken in conducting the research. The operational framework and theoretical framework of this study are also presented to illustrate the procedure.
Chapter 4: Feasible Aircraft Routes and Crew Pairs
This chapter provides two methods in generating feasible aircraft routes and crew pairs that will be used in the integrated model of aircraft routing and crew pairing problems. The comparison between both methods is presented in terms of computational time and solution quality.

Chapter 5: Exact Approaches for the Integrated Model of Aircraft Routing and Crew Pairing Problems
This chapter provides the exact approaches used in solving the integrated model of aircraft routing and crew pairing problems. There are three approaches which are integer linear programming (ILP), Benders decomposition and Dantzig Wolfe decomposition method. These models are then solved by using Microsoft Visual Studio C++ interface with libraries for mathematical programming, ILOG CPLEX Callable Library. The performances of the methods are compared.

Chapter 6: Heuristic Approach for Solving the Integrated Model of Aircraft Routing and Crew Pairing Problems
In this chapter, model of integrated aircraft routing and crew pairing problem is solved using a heuristic method which is particle swarm optimization. The model is then solved by using MATLAB. The comparisons of the results between all methods are also presented in this chapter.

Chapter 7: Summary and Future Research
In this final chapter, a brief review of the entire research work is presented. Additionally, some future research avenues that are worthwhile investigating in the future are also outlined.
REFERENCES


Ruther, S. *Integrated Aircraft Routing, Crew Pairing, Tail Assignment.* PhD thesis. The University of Newcastle, United Kingdom; 2013.


