

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

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PAIRING PROBLEM WITH SHORT FLIGHT LEGS

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*To my late father, mother, husband and family for their never ending support and care*

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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.

## ABSTRAK

Masalah laluan pesawat dan masalah pasangan anak kapal adalah dua proses yang sukar untuk diselesaikan dalam operasi perancangan penerbangan disebabkan oleh peraturan yang setiap penerbangan perlu dikendalikan oleh satu pesawat dan sepasukan anak kapal. Kedua-dua masalah ini, walaupun berkait dalam praktik, kebiasaannya diselesaikan secara berurutan dan selalunya membawa kepada penyelesaian suboptimum. Oleh itu, penyelidikan ini menyumbang kepada penyelesaian masalah bersepadu antara laluan pesawat dan pasangan anak kapal untuk menentukan kos masalah bersepadu yang paling minimum di mana setiap penerbangan dijalankan oleh satu pesawat dan sepasukan anak kapal. Kajian ini turut mengambil kira sambungan pendek antara dua penerbangan bagi memastikan anak kapal tidak menukar pesawat jika jurang masa sambungan di antara 20 minit hingga 59 minit. Pertimbangan lain yang turut diambil kira adalah sambungan terhad yang mengenakan kos penalti apabila penerbangan kedua menggunakan pasukan anak kapal yang sama tetapi pesawat yang berbeza. Berdasarkan kajian sorotan, kebanyakan penyelesaian yang sedia ada tertumpu kepada pengurangan kos terancang. Walaupun kos minimum sangat penting dalam perancangan operasi penerbangan, namun kecekapan kaedah penyelesaian dari segi masa pengiraan tidak boleh diabaikan. Ia adalah satu keperluan untuk menyelesaikan masalah bersepadu dengan menggunakan model yang efektif yang boleh menjana penyelesaian berkualiti tinggi dalam masa yang singkat sebagaimana permintaan industri penerbangan. Untuk menyelesaikan masalah ini, satu set laluan pesawat boleh laksana dan pasangan anak kapal perlu dijana terlebih dahulu untuk digunakan sebagai data input dalam menyelesaikan model bersepadu secara berkesan. Terdapat dua kaedah heuristik yang dicadangkan dalam penjanaan set laluan pesawat boleh laksana dan pasangan anak kapal, iaitu heuristik membina dan Algoritma Genetik (AG). Laluan pesawat dan pasangan anak kapal yang telah dijana, kemudiannya digunakan untuk menyelesaikan masalah bersepadu dengan menggunakan kaedah Pengaturcaraan Linear Integer (ILP), kaedah Penguraian Dantzig Wolfe, kaedah Penguraian Benders dan *Particle Swarm*. Keputusan pengiraan yang diperoleh daripada kaedah-kaedah ini kemudiannya dibandingkan dengan menguji mereka ke atas empat jenis pesawat dengan jumlah penerbangan yang berbeza berdasarkan penerbangan tempatan Malaysia bagi tempoh kitaran penerbangan satu minggu. Berdasarkan keputusan berangka, boleh dirumuskan bahawa kaedah yang dicadangkan lebih berkesan berbanding kaedah ILP dalam kajian sorotan dari segi masa pengiraan di mana algoritma hibrid AG dan Penguraian Benders didapati berkelebihan berbanding dengan kaedah lain. Sisihan kos maksimum yang hanya 4.77% juga memberi justifikasi kekuatan algoritma hibrid ini. Satu kajian masa depan yang mungkin boleh diperluaskan daripada kajian ini adalah penghasilan algoritma yang menggabungkan AG selari di dalam kaedah yang dicadangkan untuk keadaan yang lebih besar yang berkemungkinan wujud dalam penerbangan antarabangsa untuk mempercepatkan proses perancangan.

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**LIST OF ABBREVIATIONS**

ATAG	-	Air Transport Action Group
IATA	-	International Air Transport Association
NP	-	Non-deterministic polynomial-time
ILP	-	Integer linear programming
MILP	-	Mixed integer linear programming
RMP	-	Restricted master problem
LP	-	Linear programming
GA	-	Genetic algorithm
KLIA	-	Kuala Lumpur International Airport
KUL	-	Kuala Lumpur
BKI	-	Kota Kinabalu
KCH	-	Kuching
JHB	-	Johor Bahru
LGK	-	Langkawi
PEN	-	Penang
MKM	-	Mukah
KUD	-	Kudat
SDK	-	Sandakan
BTU	-	Bintulu
LBU	-	Labuan
MYY	-	Miri
SBW	-	Sibu
TWU	-	Tawau
LDU	-	Lahad Datu
TGG	-	Kuala Terengganu
KUA	-	Kuantan

AOR	-	Alor Setar
KBR	-	Kota Bharu
AT	-	Actual time
FT	-	Flying time
PC	-	Pressure cycles
RM	-	Ringgit Malaysia
CHM	-	Constructive heuristic method
M1	-	Integer linear programming model
M2	-	Benders decomposition model
M3	-	Dantzig Wolfe decomposition model
PSO	-	Particle swarm optimization
CHM_M1	-	Constructive heuristic method of M1
CHM_M2	-	Constructive heuristic method of M2
CHM_M3	-	Constructive heuristic method of M3
CHM_PSO	-	Constructive heuristic method of PSO
GA_M1	-	Genetic algorithm of M1
GA_M2	-	Genetic algorithm of M2
GA_M3	-	Genetic algorithm of M3
GA_PSO	-	Genetic algorithm of PSO

## 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
$v_\varphi$	-	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
$\varrho$	-	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
$P_\Delta$	-	Set of extreme points
$R_\Delta$	-	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

$u_i^r$	-	Extreme ray
$u_i^p$	-	Extreme point
$\varepsilon$	-	Arbitrary tolerance
$\square$	-	Integer numbers set
$\square$	-	Real numbers set
$v$	-	Velocity

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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.

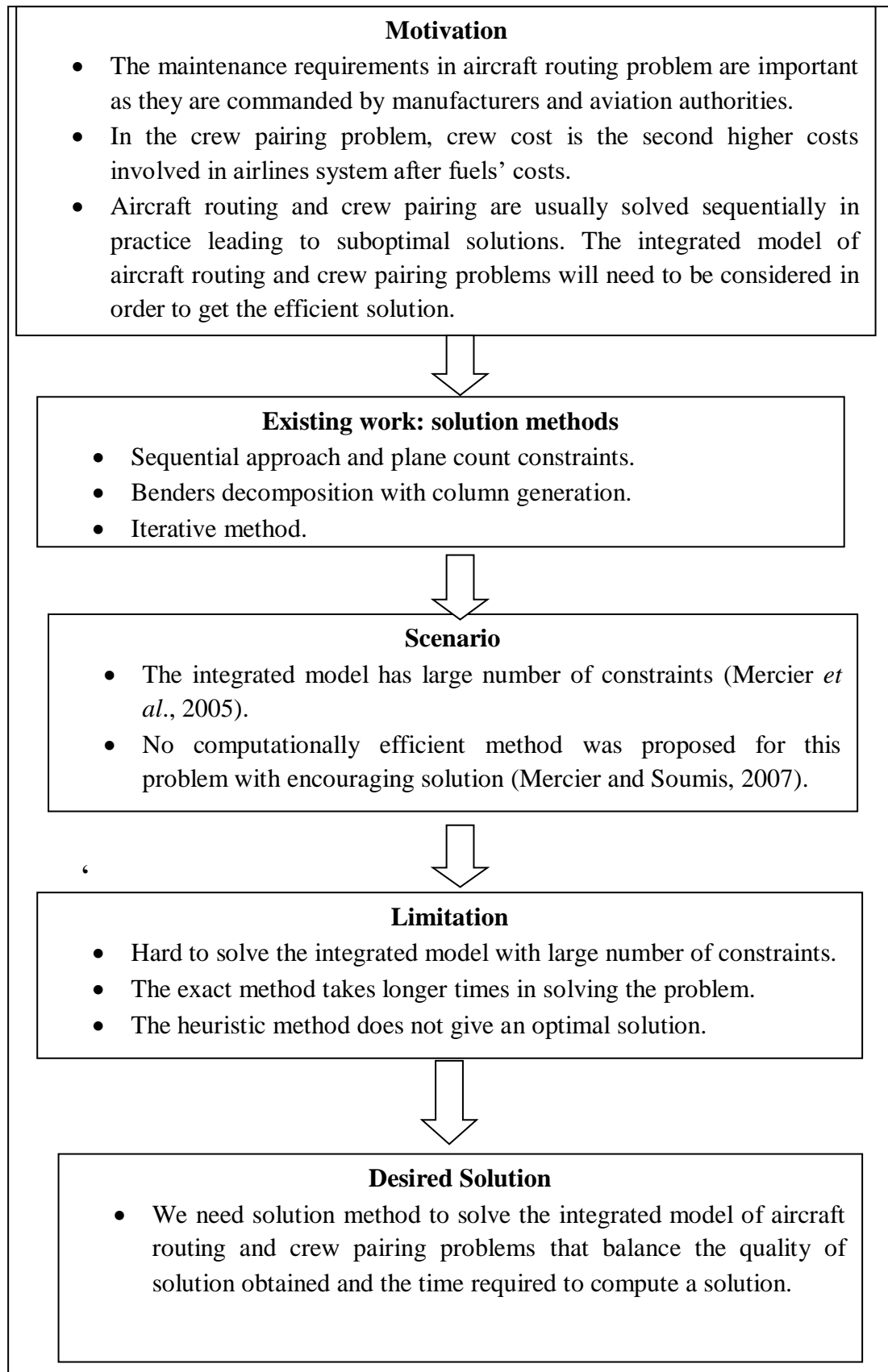
As airlines manage hundreds of aircrafts and hire thousands of workers, they encounter complicated decision making processes along the planning procedure. The planning procedure cannot be made concurrently due to the higher number of airlines planning process involved. Traditionally in airlines, a sequential 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 Kliwer (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.



**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.

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