THE AIR CARGO SCHEDULING PROBLEM WITH HETEROGENOUS FLEET

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ABSTRACT

THE AIR CARGO SCHEDULING PROBLEM WITH HETEROGENOUS FLEET

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In this study, we consider the Air Cargo Scheduling Problem based on a real life application. The aim is to move cargo and passengers that have different priorities and delivery time window, from a number of origin airports to destination airports by means of a transportation system. The system has predefined carrier routes and a heterogeneous fleet of aircraft. The problem is formulated as a heterogeneous vehicle, multi commodity, pick-up, and delivery network flow problem with a large set of system specific constraints. The proposed model determines set of movement requirements assigned on each route leg and number and type of aircraft assigned for each route in a reasonable amount of time. The model is tested with the real and generated data and the results are compared with the current methodology under different scenarios. The model produced better results in a short amount of time compared to the current methodology.

Keywords: Air Cargo Scheduling, Network, Pick-Up and Delivery, Time Windows, Heterogeneous Vehicle Fleet

ÖZ

HETEROJEN ARAÇLI
HAVA KURYESİ ÇİZELGELEME PROBLEMİ

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Bu çalışmada, gerçek bir uygulamadan yola çıkılarak, Hava Kuryesi Çizelgeleme Problemi ele alınmıştır. Çalışmada değişik önceliklere ve teslim sürelerine sahip kargo ve yolcuların, başlangıç havaalanlarından varış havaalanlarına bir taşıma sistemi vasıtası ile ulaştırılması hedeflenmiştir. Sistem daha önce tanımlanmış rotalardan ve değişik özelliklere sahip uçaklardan oluşmaktadır. Problem sisteme özgü geniş bir kısıt kümesi üzerinden heterojen araçlı, çok ürünlü, toplama ve dağıtımlı ağ akış problemi olarak modellenmiştir. Önerilen model her bir rota bacağında taşınacak olan taşıma istekleri kümesini ve her bir rotada kullanılacak olan uçakların miktarını ve cinsini makul bir zaman dilimi içerisinde belirlemektedir. Önerilen yöntem gerçek ve sonradan üretilen veriler kullanılarak test edilmiş ve halihazırda kullanılan yöntemle değişik senaryolar altında karşılaştırılmıştır. Önerilen model ile halihazırda kullanılan yönteme göre çok daha kısa bir zaman içinde daha iyi sonuçlar üretmiştir.

Anahtar Kelimeler: Hava Kargo Çizelgelemesi, Ağ, Toplama ve Dağıtma, Zaman Penceresi, Heterojen Araç Filosu

To My Love and Sweet Daughter

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TABLE OF CONTENTS

CHAPTER

APPENDICES

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

In this thesis, we study the Air Cargo Scheduling Problem (ACSP) that is based on a real life application. The objective is to move cargo and passengers based on a weekly flight schedule from a number of origin airports to destination airports by means of a transportation system that has predefined carrier routes, flight schedules and a fleet of aircraft with different characteristics. In other words, given the weekly movement requirements for both cargo and passengers (i.e., commodities) and available aircraft and airport resources, the aim is to find the best combination of commodities, routes, and aircraft types to meet the requirements subject to system specific constraints. The ACSP can be formulated as a multi objective, multi vehicle, multi commodity, pick-up and delivery network flow problem with a large set of specific constraints.

Below we discuss distinguished characteristics of our problem. First of all, we have a heterogeneous fleet of aircraft with different characteristics. Second, we impose a time window for the delivery of commodities. Therefore, selected commodities should be transported to designated destinations within assigned time windows. Third, the commodities we move have prespecified priorities that impose different service levels for each priority class. For instance, some requests should be met at the specified delivery date while some other requirements can be postponed and delivered after their specified date. Finally, passengers and cargo loads (i.e., commodities) are carried together at the same cabin and the total amount that an aircraft can carry depends on the number of passengers and the amount of cargo to be carried. In ideal conditions this requires the solution of a commodity loading problem for each aircraft during solving the scheduling problem to find out the best configuration of load assignments that affects capacity usage, the route assignments, and service quality. Therefore, the ACSP considered here differs from the other studies in the literature.

In this chapter, we explain the motivation behind our study, describe the problem, and provide an outline of the thesis.

1.1 Motivation

Air transportation is one of the most critical components of supply chains. It is extremely important especially for the transportation of emergency deliveries, shortages, perishable goods, and critical components. Air cargo system has many benefits over other modes of transportation such as speed of delivery, secure handling of the commodities, and geographic flexibility like flying overseas. On the other hand, the main disadvantage is comparatively high transportation costs compared to ground and sea transportation.

According to World Air Cargo Forecast 2012-2013 of Boeing, during the next 20 years, demand for air cargo services will double and correspondingly the number of airplanes in the worldwide freighter fleet will increase by more than 80%. According to the report, scheduled air cargo traffic accounts for 90-93% of all world air cargo. Most shippers try to use regularly scheduled cargo capacity to meet their transportation requirements mainly because of paying less for transportation. The remaining 7-10% of world air freight transport is provided to meet urgent requirements or special needs. (World Air Cargo Forecast, 2012)

Although the cost incurred in air cargo transportation is generally higher than ground or sea transportation, there are numerous advantages of air transportation over others as mentioned above. The most important advantages that are usually considered by customers are speed and frequency. These factors turn out to be much more significant in mode selection if the requirements are urgent. Also, short transportation times and tight control procedures applied on air cargo services reduce the probability of damage and theft, which makes air transportation more secure. Another important characteristic of air transport is reliability of the services provided as arrival and departure times are being highly accurate compared to other modes of transportation. Finally, the capital is not tied up in the long transit times as air cargo is delivering much faster than ground or sea transportation.

These advantages are surely accompanied by some difficulties. The most important problems encountered are:

(a) determination of fleet size and mix,

(b) design of the service network such as selection of airports to depart from and arrive at, forming routes between these airports and deciding on frequency of routes,

(c) assignment of aircraft and their crews to the determined routes,

(d) selection of which set of requirements to be accepted for moving, and

(e) assignment of these selected requirements to the aircraft and routes.

All of these main decision problems can be handled by an effective planning and decision making process. In order to minimize transportation expenditures while operating and maintaining an efficient, effective, punctual, and sustainable transportation network, building and maintenance of a well-composed transportation network is necessary. However, they may not guarantee smooth operation unless it is supported by an effective decision making process at the operational level. In this sense, models and tools developed for air cargo systems not only will help evaluation of investment alternatives, but also they will help to form effective flight plans and schedules in a short amount of time that minimizes costs while maximizing delivered commodities on time and increasing the service quality.

There are several studies conducted in the area of air cargo planning in the literature. Some of these studies concentrated on the strategic level decisions such as determination of fleet size and mix and other investment alternatives. Some other studies try to design air cargo network by determining airport set and frequency of routes between these airports plus to determine set of accepted requirements, routes, and aircraft combinations at the operational level. However, because of the fact that the system under study has peculiar characteristics, none of these studies alone fully covers dynamics of our problem. Therefore, it is necessary to consider specific characteristics of the system by developing an approach specific to the problem environment under consideration.

1.2 Problem Statement

In this thesis we study the multi-commodity heterogeneous vehicle air cargo network problem for dealing with operational level decisions such as which customer requirements would be accepted, which routes would be used for deliveries of accepted requirements, and which aircraft combinations would be scheduled on a particular day. All these operational decisions support tactical and strategic level decisions to identify current system performance according to given performance measures, namely, capacity usage of route legs and aircraft. Below we define the inputs, objective function, constraints, and outputs of the problem, considering the system under consideration.

Inputs

For the movement requirements we have information about origin node, destination node, release time, delivery time window and latest delivery time, cargo weight, cargo volume, number of passengers, and priority attributes. For the aircraft we have information about speed, variable and fixed cost, maximum load and passenger capacity, available number of aircraft, fuel consumption rate, and loading efficiency parameters. For routes we have information about route legs, airports, distances between airports, and schedule related attributes like takeoff and landing time of the aircraft to each airport on a route. Finally we have service level parameters for each priority class. The schedule of the incoming week is prepared on Friday and the first flight is scheduled on Monday morning. Therefore the movement requirements should be submitted before Friday. However, there are also cases in which requirements are submitted during the planning week to be met at that week.

Parameters of aircraft are derived from the technical manuals of the aircraft. The supply of aircraft for each route is a tactical level decision and except the urgent cases, the available supply of aircraft is used as input during the schedule planning process. Routes and service levels are again determined at the tactical level and provided as input for the decision process.

Objective Function

The objective is to move a number of weekly movement requirements by using a fleet of aircraft economically and effectively. By economically, we mean the least possible transportation cost. By effectively, we intend to improve or increase the satisfaction of certain service levels for commodities. Priority classes determine the value of the requirements according to company service costs. The one that has high priority is more critical than those with lesser priority. Service levels are specified according to this classification and critical commodities have greater service level.

Constraints

First of all, we need to satisfy flow conservation and route conservation constraints for controlling the flow between airports according to prescheduled route structure. We have capacity constraints to satisfy weight and volume of cargo loads, the number of passengers and takeoff weight capacities of the aircraft. In our system, passengers and cargo are carried together at the same cabin and the amount of commodities that an aircraft can carry depends on the number of passengers and the amount of cargo to be carried. Therefore, the problem also requires the solution of a commodity loading problem for each aircraft before scheduling. Finally, we have restrictions on the number and types of aircraft that can be used for each route according to supply of the aircraft. Note that there are a number of airports that serve as source nodes for the aircraft and these airports are also the origins of the routes. The aircraft, aircrews, technical staff, and maintenance facilities are located in the airports where the routes originate and terminate.

Outputs

The main decisions given in the problem are set of movement requirements scheduled for transportation, set of movement requirements assigned on each route leg on a day, and number and type of aircraft assigned for each route on a day. Therefore, we actually determine the best requirement, aircraft, and route combinations in the problem. Also, corresponding costs for these decisions are another output of the system.

Although the total cost is the most distinct performance measure, satisfaction of service levels and number of orders scheduled for transportation are other performance measures.

The content of the thesis is structured as follows. In Chapter 2, we present a review of studies in the air cargo literature that are related with our problem. In Chapter 3, first we describe the air cargo system and Iterative Scheduling Methodology (ISM), and then explain proposed methodology and air cargo scheduling model (ACSM). In Chapter 4, we provide the mathematical formulation of the ACSM and in Chapter 5 we give the computational results. Finally in Chapter 6, we conclude the study with a summary of our major contributions and a few ideas on possible directions for future research.

CHAPTER 2

LITERATURE REVIEW

As in most of the business processes, planning levels in transportation systems can be divided into strategic, tactical and operational levels. At the strategic level, system-wide long-term decisions are given for transportation network design, location of facilities, and investment alternatives. Tactical level decisions cover medium-term decisions and activities such as design of service network, determination of routes, and allocation of resources to these routes. At the operational level, short-term decisions are given for scheduling crews, services, and maintenance activities, and routing of vehicles. For all planning levels, there exists a huge body of literature. Within the scope of this thesis, a deductive approach is used for the literature survey in a way that we start from the general studies and move on to more specific studies that are closely related with our problem.

In this chapter first, a classification of transportation systems is provided. According to this classification scheme, tactical and operational level problems that are related to our study are introduced. Similarities and differences between each given problem and our problem are discussed. Finally, the three-dimensional bin packing problem is presented and relation with our problem is explained.

2.1. Transportation Systems

Crainic (2003) classifies transportation systems into two as customized/door-to door transportation and consolidation/service transportation. Main characteristics of these classes are presented in Figure 2.1.

Customized/Door-to-Door Transportation	**Consolidation/Service Transportation**
Services are adjusted according to specific needs of the customers.	Several customers are met simultaneously by using the same mode of transportation.
The vehicle with driver and unloading team is assigned to the customer.	Transportation network has regular schedules/routes to maximize the number of customers served.
There exists little information for future demands, origin-destination pairs, and delays.	The schedules and routes are announced to the customers beforehand.

Figure 2.1 Classification of Transportation Systems

Customized/Door-to-Door Transportation

In customized/door-to-door transportation, transportation services are adjusted according to specific needs of the customers. Truckload Trucking (TL) is one example of door-to-door transportation, which arises in distributing goods over long distances. In TL transportation a truck with driver and unloading team is assigned to the customer. They arrive to the designated customer location at the required time. After loading operation they move to the specified destination. After unloading operation at the destination there exist two alternatives. Either, they wait for a new assignment or they are assigned another customer at another location, so they move to the new specified location. As a result in TL transportation, there exists little information for future demands, origin-destination pairs, and delays.

Consolidation/Service Transportation

In this type of transportation, demands of several customers are met simultaneously by using the same mode of transportation. The services are not tailored to specific needs of customers as in the door to door transportation. The objective is to design a transportation network that has regular schedules and routes in order to maximize the number of customers that use the service. In this type of transportation, origin, destination, and intermediary stops, departure/arrival times from/at origin/ intermediary stops, and capacity parameters are determined and proposed to the customers. Less-than-truckload trucking companies, railways, shipping lines, and postal and express shipment services usually offer this type of transportation service.

At this point it is useful to differentiate between moving people and freight. The above classification is valid completely for freight transportation, but only some operating characteristics can be applied for moving people. The most significant difference between these two modes of transportation is related with planning horizon. In passenger transportation, companies plan fixed schedules over fixed routes. The customers arrange their plans by using these schedules. Except reasonable conditions, it is usually not possible to change the flight schedules. Freight transportation, on the other hand, operates in a more dynamic environment and operation plans need to be modified frequently in case of new transportation requirements. Therefore, flight schedules are not as precise as passenger transportation.

According to this classification, our problem is in the consolidation/service transportation class. In our system, demands for moving people and freight are met simultaneously by using same set of aircraft and route combinations. In our system there exists a transportation network that runs at regular weekly schedules and routes, usually applied for a long-period of time with limited modifications. The customers are informed beforehand about the routes and their schedules.

Agarwal and Ergun (2008) state that strategic level decisions are extremely important as the decisions regarding the optimal number and mix of vehicles for a fleet design are made at this stage. They also argue that the decisions given at the strategic level determines the general policies, strategies, and guidelines for the tactical and operational levels. Similarly, tactical level decisions set limitations on the network structure and capacity level for the operational level planning. Because of the fact that our problem is an operational level problem, after this point we will concentrate on operational level problems.

2.2 Vehicle Routing Problem (VRP)

The Vehicle Routing Problem (VRP) concentrates on distribution of goods from depots (supplier) to final users (customers) or vice versa. In the VRP we are concerned with distribution of commodities by means of a transportation network to the customers that are usually dispersed in a geographic region. There are a set of vehicles and their crews located in one or more depots in a given time period. In solving the VRP, while we are minimizing total transportation costs, we determine a set of routes, each performed by a single vehicle that starts and ends at its own depot. In this way all customer requirements are fulfilled and all operational level constraints are satisfied.

Several variants of the VRP have been studied in the literature depending on the features of the problem environment. When we impose upper bounds on the vehicle capacities, the problem is called the Capacitated Vehicle Routing Problem (CVRP). The basic CVRPs and their interconnections, which are adapted from Toth and Vigo (2001), are illustrated in Figure 2.2.

In the CVRP demands and deliveries are deterministic and cannot be split. The vehicles are identical, capacitated, and located at central depot. The objective is to minimize total cost of serving all customers. If we constrain the maximum distance that can be travelled by vehicles, then the problem is called as the Distance Constrained VRP (DCVRP).

The VRP with Time Window (VRPTW) is an extension of the CVRP in which the service at each customer must start within an associated time window and the vehicle must remain at the customer location during the service. (Cordeau et al., 2001)

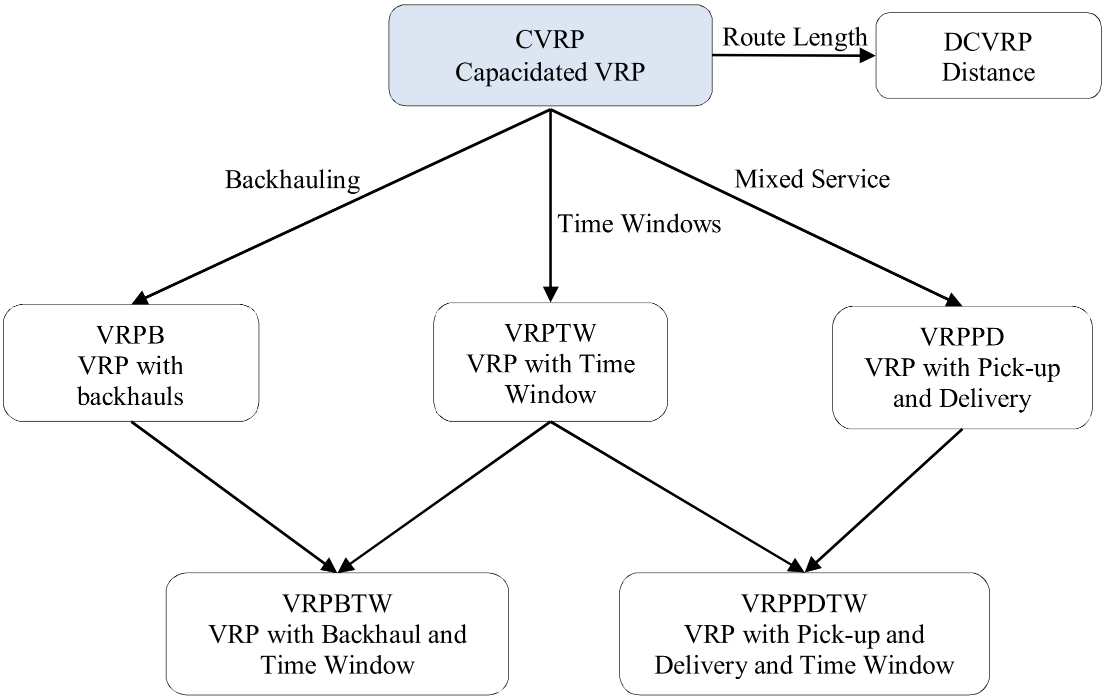

Figure 2.2 The Basic Classes of the VRP and Their Relations

The VRP with Backhauls (VRPB) is another extension of the CVRP in which the customer set is partitioned into two subsets. The first subset contains only linehaul customers, each requiring a given quantity of product to be delivered. The second subset contains only backhaul customers, where a given quantity of inbound product must be picked up. In the VRPB, a precedence constraint between linehaul and backhaul customers exists. When a route serves both type of customers, all the linehaul customers are served before a backhaul customer may be served (Toth and Vigo, 2001).

In the VRP with Pickup and Delivery (VRPPD), a heterogeneous vehicle fleet must satisfy a set of transportation requests. Each request is defined by a pickup point, a corresponding delivery point, and a demand to be transported between these locations. The transportation request can involve goods or persons. This latter environment is called dial-a-ride (Desaulniers et al., 2001).

The VRPPD with Time Windows (VRPPDTW) is a generalization of the VRPTW. Problems in this class involve time constraints that establish time intervals during which service must take place at each stop, or that express user inconvenience and maximum ride time restrictions for passengers. In addition to time windows to be satisfied at each stop, the VRPPDTW involves several other sets of constraints. These are visiting each pickup and delivery stop exactly once, not exceeding the vehicle capacity, coupling pickup and corresponding delivery stops on the same vehicle route, imposing visit precedence relations among pickup stops and their associated drop-off stops. There are also depot related constraints that ensure vehicles to return to the appropriate depots and resource restrictions on the number of drivers and vehicle types (Desaulniers et al., 2001).

The VRPPDTW has a variety of practical applications, including transport of disabled and elderly people, sealift and airlift of cargo and troops, and pickup and delivery overnight carriers. Perspectives on this growing field are discussed in Solomon and Desrosiers (1992), Desrosiers et al. (1995), and Savelsbergh and Sol (1995). The class of the VRP with pickups and deliveries dealing specifically with passenger transportation is known as dial-a-ride problems. A discussion of modeling issues in dial-a-ride problems and an overview of proposed algorithms can be found in Cordeau and Laporte (2003). Espinoza et al. (2008) presents an integer multi-commodity network flow model with side constraints for the dial-a-flight problems. When dealing with passenger transportation, service-related constraints and objectives have more significant roles. Dial-a-flight and dial-a-ride problems have many common characteristics. However, there are also some notable differences. The dial-a-ride problem often arises in social services contexts, e.g., transportation of the elderly, whereas the dial-a-flight problem is encountered exclusively in business settings. As a result, there tends to be less flexibility in the specification of requests, especially in terms of the desired service level in dial-a-ride environments. Furthermore, in dial-a-ride environments, requests often have a common destination or a common origin (e.g., to visit a hospital, or to go to the mall), whereas in dial-a-flight environments such cases rarely happens.

From the VRP perspective, our problem has characteristics that best suit to multi-commodity, multi-depot, heterogeneous vehicle pickup and delivery problem with time windows. This problem is one of the most complicated classes of the VRP. In addition to these main characteristics, our problem has other properties that have not been addressed in the VRP literature. For example, we have not only heterogeneous vehicles with different characteristics, but also different capacity configurations for each vehicle type that depend on the number of passengers and amount of cargo carried plus a large set of capacity constraints regarding total weight, takeoff weight, volume, plate, and passenger configurations that change from vehicle to another. On the other hand, some decisions and constraints of the VRP are not considered in our problem environment. For example, the routes and their schedules are fixed in our problem contrary to finding routes for vehicles for a set of stopping points in the VRP.

Other than the VRP, there exist a few studies in the literature that have similar characteristics with our problem. These problems are called Container and Liner Shipping Problems and Air Cargo Network Planning Problems.

2.3 Container and Liner Shipping

Container and Liner Shipping is for carrying containerized cargo on regularly scheduled service routes. The frequency required on a service route, the distance travelled by a ship on the service route, and the ship speed determine the number of ships required for a given liner service route.

Rana and Vickson (1991) provide a nonlinear integer program to maximize total profit. They try to find an optimal sequence of ports to visit for each containership and an optimal number of cargo units to be transported between each pair of ports by each ship. They allow multiple pickups and deliveries on their ships. However, they do not allow loading and unloading of cargo at the end ports. Furthermore, their model does not allow transshipments.

Fagerholt (1999) presents a liner shipping model, based on solving a set partitioning problem where all cargo is transported from a set of production ports to a single depot. The model does not allow for transshipments.

Petrakis (2002) presents a review of liner and integer programming models that consider deployment of a fleet of liner ships with different ship types on a set of given routes with targeted service frequencies to minimize costs.

Agarwal and Ergun (2008) present a mixed-integer linear program to solve the ship-scheduling and the cargo-routing problems, simultaneously. The proposed model incorporates relevant constraints such as a weekly frequency constraint on operated routes and transshipment possibility for cargo between two or more service routes. They propose algorithms that exploit separability of the problem.

Our problem has similarities with Container and Liner Shipping. Both solve the problem of carrying containerized cargo on regularly scheduled routes. Both allow multiple pickups and deliveries. However, there are several differences between the two problems. For instance, in our problem, in addition to cargo, passengers should be carried between airports. Besides, transshipments of commodities for a subset of airports are allowed. By transshipment we mean that the exchange of cargo and passengers between different routes and aircraft is possible when their stops meet at an airport.

2.4 Air Cargo Network Planning Problem

Among all studies considered up to now, the air cargo network planning problem is the most similar problem to ours.

Etschmaier and Mathaisel (1985) present the concept of iterative planning process, composed of two phases: schedule construction and schedule evaluation. In schedule construction, a central scheduling department develops a draft schedule, which is then evaluated by various operating departments in terms of feasibility, cost, and economic value. Based on these evaluations, the draft schedule is revised and modified until a feasible schedule is obtained.

Yan, Chen, and Chen (2006) study an integrated scheduling model for solving the airport selection, fleet routing, and timetable setting problem. Given a set of projected cargo demand, their model maximizes profit subject to operating constraints.

Derigs et al. (2009) formulate two integrated models that combine the three planning steps: flight selection, aircraft rotation planning, and cargo routing. The aim is to maximize the network-wide profit by determining the best combination from a list of mandatory and optional flights, assigning the selected flights to aircraft and identifying cargo flows. Both model formulations are embedded in a solution procedure that is built on the column generation technique using shortest path algorithms for solving the sub-problems.

Air Cargo Network Planning studies have some commonalities with our problem. Although their models are mostly built for profit seeking air cargo organizations which have different operating characteristics and objectives compared to our problem environment. They try to assign a set of requirements to a set of aircraft and then to assign these aircraft to the scheduled flights. The objective is to minimize the total cost or to minimize the number of aircraft assigned. Despite these similarities, the following differences can be mentioned. First, our problem environment has different types of aircraft with different characteristics. Second, it imposes a time window for deliveries. Selected commodities should be transported to designated destinations within given time window. Third, the commodities have priorities and there are service level constraints that impose different service levels for each priority class. Finally, in our problem, passengers and cargo are carried together at the same area and the amount of commodities an aircraft can carry is based on the number of passengers and the amount of cargo.

To sum up, our problem has similarities or decision overlaps with the VRP, the container and liner shipping problem, and the air cargo network planning problem. However, none of these problems alone fully fit our problem environment. Therefore, we introduce the air cargo scheduling problem to find the best combination of commodities to carry at a day and routes and aircraft types to be used at a day given the weekly movement requirements for both cargo and passengers, and available aircraft and airport resources.

2.5 The Three-Dimensional Bin Packing Problem (3D-BPP)

In this problem the objective is to pack a set of rectangular-shaped items in different sizes in terms of height, width, and depth into the minimum number of three dimensional containers. The 3D-BPP is strongly NP-hard because it is a generalization of the one-dimensional bin packing problem (1D-BPP) (Martello, Pisinger, and Vigo, 2000). Scheithauer (1991) presents an approximation algorithm for the 3D-BPP. A more general case where the bins may have different sizes is studied by Chen et al. (1995). An exact algorithm for filling a single bin is developed by Martello, Pisinger, and Vigo (1998), which leads to an algorithm for the 3D-BPP.

In our problem environment, there are different types of commodities that have different dimensions. These items should be packed into a number of plates with different dimensions depending on aircraft type, which requires the solution of the 3D-BPP for each aircraft type to find the best commodity assignment to aircraft and routes. Since 3D-BPP is strongly NP-hard, to solve a set of bin packing problems for each route leg increases the complexity of the solution procedure. Instead we propose a volume efficiency factor to produce approximate solutions for the 3D-BPP, which will be discussed in detail later.

CHAPTER 3

PROBLEM FORMULATION

The movement of commodities by aircraft is one of the most preferred modes of transportation, because it is quick, convenient, and secure. Especially, transportation of costly, light, and delicate goods by air is desirable. However, costs of air transportation are higher compared to other modes of transportation like sea or ground transportation. Therefore in order to reduce transportation costs, we need an effective method to assign aircraft to the available routes, and schedule the movement requirements to these aircraft and route pairs. This can be achieved by means of an effective planning process. In this part of the thesis, first, the system under consideration is introduced in details. Second, a formal definition of the problem is provided.

3.1 System Description and Iterative Scheduling Methodology (ISM)

The air cargo system under consideration has physical and conceptual entities and a set of decisions to be fixed. Physical entities are decision makers, customers, goods, airports, aircraft, and air crews, while conceptual entities are operation policies, routes, and schedules. Decisions are determination of the set of movement requirements scheduled for moving, specification of aircraft that fly and route combinations to be implemented, and assignment of customer requirements to the corresponding route legs. A representation of the system that highlights the interaction of these entities and decisions is simply illustrated in Figure 3.1. As can be seen from the figure, there are a set of airports and a set of customers assigned to these airports according to coverage area of the airports based on origin and destination points of customer requirements. Besides, there are a set of routes between airports and a set of aircrafts available for assignment. Below all the entities and their roles and their interactions within the system are explained and then the main decisions to be made are introduced.

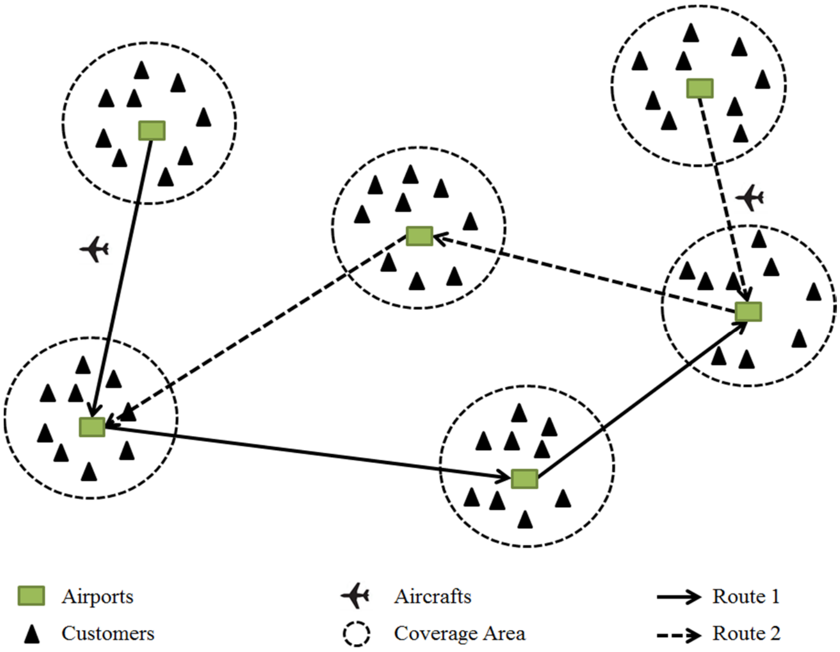

Figure 3.1 Entities of the System

Decision Makers

In the system, decisions are made at the strategic, tactical and operational levels. The decision makers at each level should interact with each other because the decisions made are dependent on each other.

At the strategic level, according to analysis of tactical and operational level related data, investment alternatives are evaluated and specified. For example, acquisition of new aircraft and changing the current fleet size are examples of such strategic level decisions. (Agarwal and Ergun, 2008)

At the tactical level, operational level statistics are analyzed and the routes, their frequencies, and available aircraft set that would be used in each route are determined according to results of these statistics.

Finally at the operational level, the submitted movement requirements from customers are analyzed and the set of accepted requirements together with assigned routes are determined. Also, aircraft are assigned routes according to cost and capacity considerations.

Customers

In the system under consideration, the customers are internal units of the company that are dispersed in a geographic area. Therefore, we have internal customers that are under the control of the company. Each customer is assigned to the nearest airport and transportation requirements are satisfied by means of assigned airport only. The customers should submit their movement requirements for the incoming week to the Transportation Planning Department of the company before Friday, because the schedule of the incoming week is prepared on Friday and the first flight is scheduled on Monday morning. However, in case of urgent requirements or unplanned deliveries, late submissions can be accepted by the company.

A transportation request includes information of origin and destination airports, release time, latest arrival time, weight of material, volume of material, number of passengers, and priority of the requirement. The requirements are submitted by a form which is called Time-Phased Commodity and Passenger Deployment Requirement Form. An example form is presented in Table 3.1. Each arriving order is checked, in case of incomplete, contradictory or inconsistent information, the order is sent back for corrections. If not, a requirement number is assigned and taken into consideration in the planning process.

In Table 3.1, origin corresponds to the source node and destination corresponds to terminal node for the requirement. Release time (*RT*) is the submission (or receiving) time of the order to the Transportation Planning Department of the company and an order cannot be included in the scheduling process unless the order is submitted. Available to load time (*ALT*) is the time that the commodities and passengers in the corresponding requirement are ready for deployment. Latest delivery time (*LDT*) is the latest time that the order should be ready at corresponding destination location. Weight and volume information are required for commodities only, not for passengers. Each passenger is assumed to be 110 kg including the personal belongings.

Table 3.1 Time-Phased Commodity and Passenger Deployment Table

No.	Origin	Destination	Release Time	Available Load Time	Latest Delivery Time	W (kg)	V (m^3)	Number of Passengers	Priority No.

Priority, a factor from 1 to 5, is used for prioritization of movement requirements. Although the customers assign priorities according to significance of the requirements, but the Transportation Planning Department has the right to change the priority level assigned according to flight regulations and standards. A requirement with smaller priority is more critical in terms of delivery times. Priority class 1 is the most critical priority level and it dominates others. In other words, for priority class 1 requirements we have to satisfy 100% service level and another class cannot be scheduled unless all class 1 priority items are scheduled. For other classes, again a precedence relation exists between priority classes. However, this time precedence relations are not tight as the priority class 1 items and some exceptions may occur. For instance, if there is no available space for a class 2 requirement, then it is possible to schedule a class 3 requirement that has smaller dimensions or weight, instead of scheduling the class 2 requirement.

The arriving cargo from customers are first grouped according to their destination and then packed on the plates to be prepared for the flight at the cargo packing sections of the airports. Plates are special platforms like conveyors that have different volume and weight capacities designed for air transportation.

Airports

Airports have a set of attributes such as location, maintenance facilities for aircraft, set of loading and unloading equipment and technical staff, fuel availability for different aircraft, and aircraft holding capacities. Every airport doesn’t have maintenance facilities. Therefore, only major airports serve as domain functions (home) for certain types of aircraft. The routes originate from and terminate at such major airports.

Aircraft and Air Crews

There are different types of aircraft that have different characteristics affecting speed, variable and fixed operation costs, cargo and passenger capacity, and fuel consumption rate. Passengers and cargo can be carried together at the same cabin and the amount of commodities that an aircraft can carry depends on the number of passengers and the amount of cargo to be carried. The arriving requirements are loaded on to the plates at the cargo packing section of the airports and then loaded to the aircraft by using specialized loading machines. Note that there are different types of plates for an aircraft type that have different volume and weight carrying capacities. Moreover, for an aircraft type mainly two types of plates are used, these are cargo hold plates used in the main cargo section and rear ramp plate used in the rear ramp section of the aircraft.

Each aircraft has a plate holding capacity for main cargo section while having a capacity of one plate for the rear ramp section. Main cargo section is for passenger and cargo transportation; however, rear ramp section can only be used for cargo transportation. Therefore, volume capacity can be expressed as a function of the number of plates and number of passengers. A representative volume and passenger configurations is illustrated in Figure 3.2. As can be seen from the figure we have 6 configurations depending on the number of plates. As number of passenger increases, available space for cargo and correspondingly the maximum number of plates decreases.

As we mentioned before, each type of aircraft has a corresponding home airport where the maintenance facilities are located. An aircraft starts its route from its home airport and after visiting all of the airports on its route, returns back to the home airport. Aircraft refueled at home airports before the flight. Nevertheless, most of the airports have a limited refueling capacity in case of emergency. Especially for the long routes, the aircraft has to be refueled at an intermediary airport and such an airport stop is planned before the flight. Amount of fuel is also an important decision parameter that should be considered in the capacity planning because it affects the takeoff weight of the aircraft. Therefore, total amount of weight in cargo section and total amount of fuel plus empty weight of the aircraft should be less than the predetermined maximum takeoff weight specification of the corresponding aircraft type.

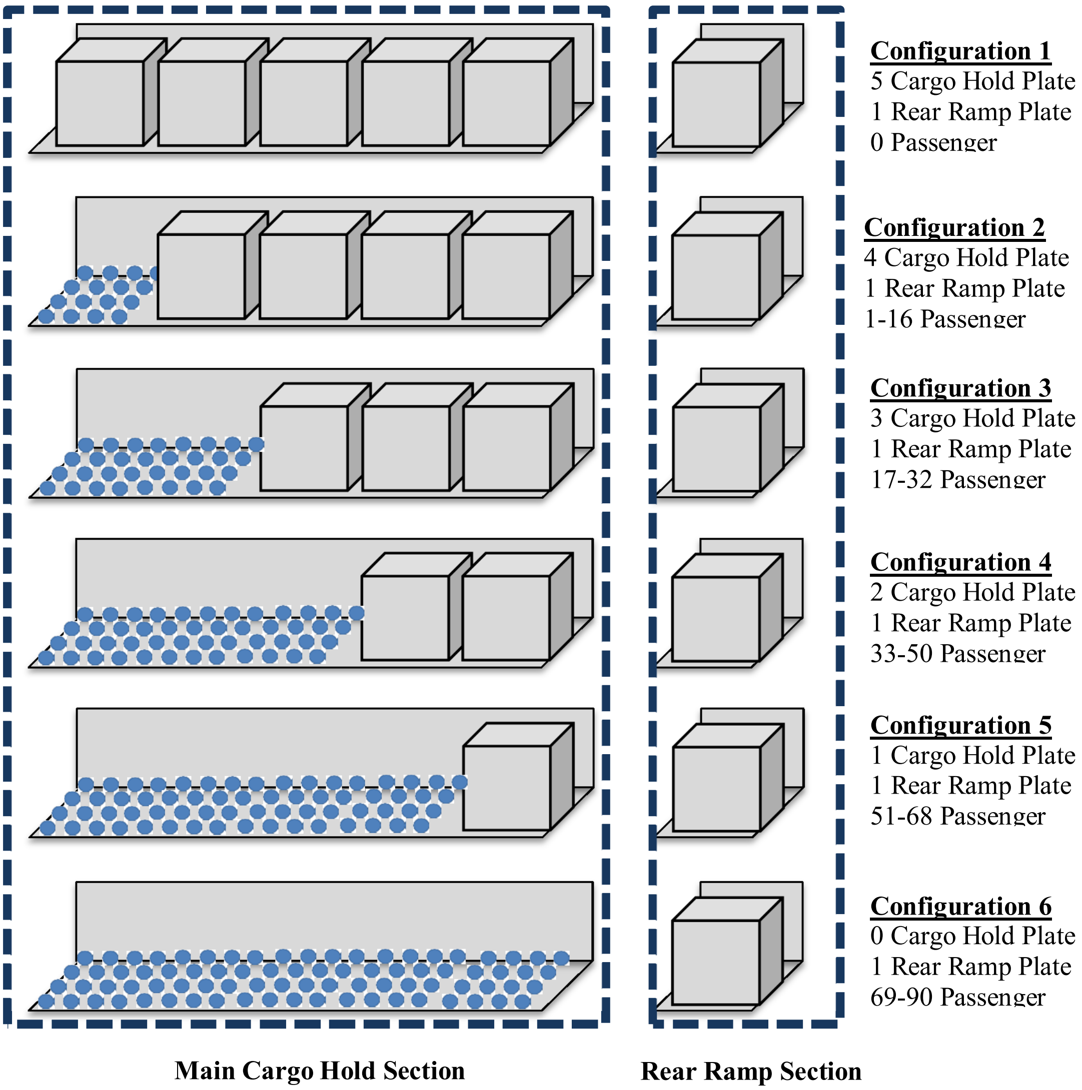

Figure 3.2 Possible Volume and Passenger Configurations for an Aircraft

The aircrew (pilots, co-pilots, and cabin personnel) also accommodated near the home airport and assigned to the flights together with the aircraft. However according to the flight regulations, the total flight hours per day a crew can spend is limited and therefore this limitation is considered in scheduling process.

Mainly, the cost is calculated according to aircraft type, based on flight hours, and composed of direct and indirect components. Direct costs include fuel, maintenance, service, flight crew, and depreciation spending. Indirect costs contain indirect personnel costs, operating costs, management and support costs. All the cost components are based on flight hours. The cost parameters are usually estimated yearly by the accounting department. Fuel cost is the critical element as it depends on many other parameters such as total weight on the aircraft, number of takeoffs and landings on a route, altitude of flight, meteorological and atmospheric conditions such as wind speed, pressure, and so on. Therefore, it requires complex calculations. Currently, the accounting department uses average cost figures based on historical reports.

Routes and Route Schedules

Routes and route schedules are determined at the tactical level and cannot be changed during operational level planning activities. The routes and schedules are determined according to historical statistics. Minor changes on routes can be incorporated annually, while major or substantial changes are for long planning periods such as once in several years. All customers know the flight schedule in advance and plan their requirements according to these schedules. This is one of the reasons that the satisfaction of service levels is high in general. The routes have different set of airports and some of the airports are contained in more than one route. On the other hand, the routes can handle different schedules planned on different days of the week. A route starts from the home airport at the beginning of working hours at that particular day of the week and terminates at another airport at midnight. The aircraft and the assigned crew should turn back home base at most in two days.

At intermediary stops the aircraft lands the airport, while loading and unloading operations are conducted, if required, the aircraft is refueled and replenished. The passengers may leave the aircraft during these processes. At the origin and destination nodes of the routes, in addition to refueling and replenishment, maintenance operations are conducted by the technical staff. The aircraft are taken to factory level maintenance, a maintenance activity that is performed after a certain amount of flight hours depending on types of aircraft and its technical standards.

Decisions

In the system there are three levels of decisions that are presented in Figure 3.3. At the strategic level, system-wide long-term decisions are made about design of transportation network, location of facilities, and investment alternatives.

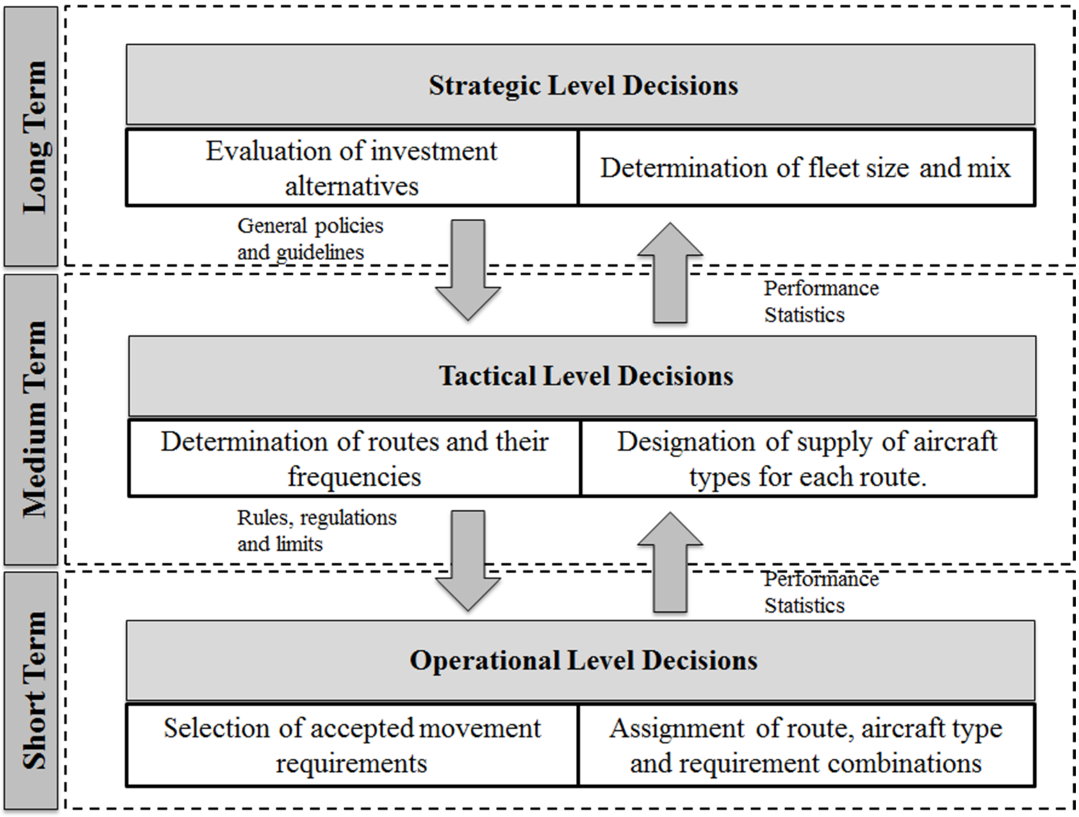

Figure 3.3 Levels of Decision Making Process

Tactical level decisions cover medium-term decisions and activities such as design of service network, determination of routes and their frequencies, and allocation of resources to these routes.

At the operational level, short-term decisions are made on selection of movement requirements, determination of route, aircraft and requirement combinations and correspondingly scheduling of crews, and aircraft maintenance activities. All the decisions are dependent upon each other. For example, performance statistics are provided from operational level to strategic level while general policies, guidelines, rules, regulations, and limits are provided from strategic level to operational level.

The decisions made at upper levels are used as inputs for the lower levels. For example routing network and available resources are defined at the tactical level. These inputs are used as the decision problem parameters of the detailed scheduling operations at the operational level.

Within the scope of this problem we concentrate on the operational level decisions based on inputs provided from other levels. A representation of the inputs, outputs and decision process at the operational level is provided in Figure 3.4. In this figure we illustrate the inputs for the decision process, decisions made, and the outputs of the decision process.

Objective of the Decision Process

In the decision model the objective is the minimization of total cost and maximization of service levels for each priority class. The total cost is composed of direct and indirect flight costs based on flight hours as explained before. Note that, the cost value is changing according to route and aircraft types.

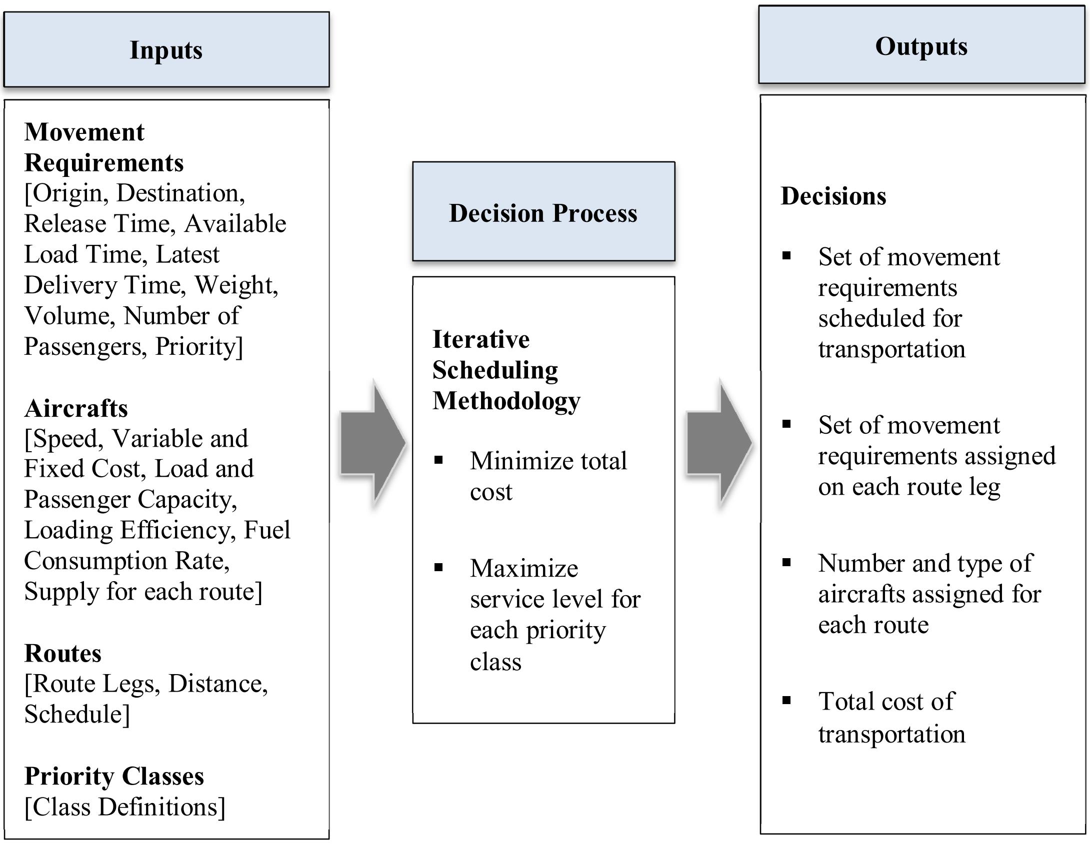

Figure 3.4 Iterative Scheduling Methodology

The other objective, "maximization of service levels" considers the number of requirements scheduled for transportation. In order to handle the problem, the orders are ranked according to their priority classes. Commodities with 1st class priorities are scheduled first. If there is available space in the aircraft, then 2nd class commodities are scheduled. The process continues in this fashion until all of the priority classes are covered. For 1st class commodities, the service level should be 100%, which implies that 1st class commodities should be scheduled. If the capacity is not sufficient to handle all 1st class commodities, then a new aircraft would be appointed for moving material and people. Unfortunately, for other classes, there is no guaranteed 100% service level satisfaction. Therefore, if there is no enough capacity for a 2nd class commodity, then the dispatcher can schedule a lower class commodity that has smaller dimensions or weight, so that it can fit the remaining capacity.

Inputs of the Decision Process

For the decision process there are some inputs as shown in Figure 3.4. The movement requirements are submitted by the customers before the scheduling process begins. After the requirements are submitted, the decision process starts. However, there are also cases in which some urgent or less urgent requirements can be submitted during the week. In order to handle this situation the scheduling process is updated according to newly submitted requirements plus the requirements that have not been transported yet.

Parameters of aircraft are taken from the technical manuals of the aircraft, historical reports and accounting department. The supply of aircraft for each route is a tactical level decision and except urgent cases, only the available supply of aircraft is used for planning process. In case of urgent situations, a new aircraft can be appointed to the routes and scheduling process is updated again. Set of routes is another input determined at the tactical level and the same routing structure is used for a long-period of time.

The routing network can be changed in case of additions of new airports or significant alterations in the distribution channels and composition of the customers. Finally, specifications for priority classes are another input for the decision process. Although, customers assign a priority class for their requirements, the Transportation Planning Department has the right and authority to change the assigned priority class of commodities according to class definitions.

Iterative Scheduling Methodology (ISM)

All provided inputs are recorded by the decision maker. Suppose that recording phase is over. Now we discuss how the current scheduling methodology works. First the requirements are ranked according to their priority classes, origins and destinations, and assigned to the routes. Second, available aircraft are assigned to the routes starting from the aircraft that incurs less cost while checking for feasibility. The aircraft capacities are checked in terms of weight, volume, passenger, plate, and takeoff "capacities". If a solution is obtained, then a new search process is executed in order to determine a better alternative in terms of costs. If a feasible solution cannot be achieved, then the requirements that can be transported by using alternative routes are searched for and the requirements are switched between routes if necessary. Whenever a feasible solution is achieved, the process terminates. If not, some of the requirements are eliminated according to priority class except 1st class commodities until a feasible solution is achieved.

This iterative process is executed by at least two experienced staff and on average it takes about one work day to produce a solution. In case of late or urgent submissions of movement requirements, they start from the available solution on hand and repeat the process again.

Outputs of the Decision Process

At the end of decision process a schedule is obtained. This schedule includes set of movement requirements scheduled for transportation, set of movement requirements assigned on each route leg and number and type of aircraft assigned for each route. It implies that the requirement, aircraft, and route combinations are set. In addition to these informative schedules, total cost of the proposed schedule is also provided as an output of the decision process.

3.2 Proposed System and Air Cargo Scheduling Model (ACSM)

Within the scope of this thesis, we have concentrated on the decision process at the operational level explained in the previous section. In this process, the decision maker collects inputs from various resources, processes them and at the end makes a set of decisions. This problem is iterated at least once a week and in case of late submissions of requirements and urgent situations, the process is repeated again. It is clear that decisions at this level are monotone and most time requiring decisions. Moreover, the produced solutions are usually suboptimal and there is a lot to do for improvement. In order to eliminate the difficulties we discussed, shorten the time required for decision making process, and obtain better assignments using OR and IE techniques, we propose an Air Cargo Scheduling Model (ACSM). The representation of ACSM is presented in Figure 3.5. In this model we have a set of inputs, decision process, and outputs discussed below.

In ACSM, air cargo decision problem solving methodology is completely changed and replaces iterative scheduling method introduced in section 3.1. This time we modified the objectives and define the objective function as the minimization of total costs. In order to preserve the multi-objective structure of the problem, we introduce service level constraints to represent maximization of service level objective. Thus, while minimizing total costs, the model will satisfy the predetermined service levels for each requirement. Below, ACSM is briefly explained. The detailed mathematical formulation of ACSM is given in Chapter 4.

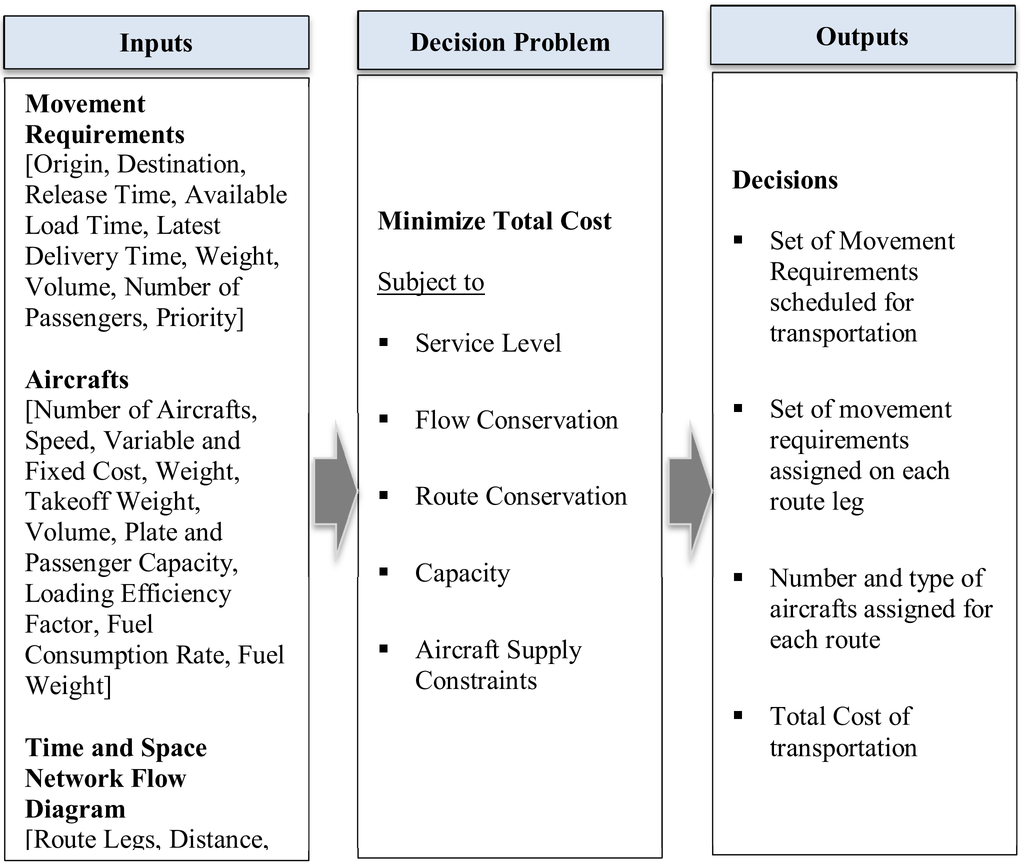

Figure 3.5 Air Cargo Scheduling Model (ACSM)

Parameters and Inputs

In each planning horizon we have *m* requirements submitted by the customers. Each requirement *m* has ten attributes. These are origin, destination, release time, available load time, latest delivery time, weight, volume, number of passengers, weight of passengers and priority.

We have thirteen parameters for each aircraft type *a*. These are number of aircraft of type *a,* speed, variable and fixed costs, weight, takeoff weight, volume, plate and passenger capacity, loading efficiency factor, fuel consumption rate, and available fuel weight.

Before constructing the model, a network diagram that has time and space dimensions should be constructed. Construction of this network diagram is the most critical and time requiring part of proposed model, as the entire problem is formulated according to this diagram. However, once constructed, it can be used for the incoming weeks after updating simply according to submitted requirements.

In the time and space network we assign labels (i,t) to nodes where i denotes the set of airports and t denotes the time. If a requirement is planned to leave airport i at time t_i and arrive at airport j at time t_j plus we have loading time l and unloading time u, then if (t_i-l) and (t_j+u) are both in $[t_s,t_f]$ interval, where t_s and t_f are the starting and finishing times of the planning horizon, then we add nodes (i,t_i-l) and (j,t_j+u) to the time and space network.

Consider each requirement *m*. Let *source(m)* denote the origin airport, *destination(m)* destination airport, *Available_Load_Time(m)* the time at which the requirement becomes available for loading, and *latest_arrival_time(m)* the latest arrival time of the requirement to the destination airport. For all these requirements, we add source and sink nodes such that

$$[Source\ (m),\ max\ \{Available\_Load\_Time(m),\ t_s\}]$$

$$[Destination\ (m),\ min\ \{Latest\_Arrival\_Time(m),\ t_f\}]$$

Where *Source(m)* and *Destination(m)* represents the location components and $max\{Available\_Load\_Time(m),t_s\}$ and $min\{Latest\_Arrival\_Time(m),t_f\}$ represent the time components of the nodes. For source nodes we take the maximum of *Available_Load_Time(m)* and t_s, while for the destination nodes we take the minimum of *Latest_Arrival_Time(m)* and t_f.

The nodes that have the same label (i,t_i), only one of them is included in the network and the others are deleted. After determining all nodes of the network, then the necessary arcs of the network are added. If a requirement is planned to leave airport i at time t_i and arrive at airport j at time t_j plus we have loading time l and unloading time u then if (t_i-l) and (t_j+u) are both in $[t_s,t_f]$ interval, where t_s and t_f are the starting and finishing times of the planning period, then we add the capacitated arcs from nodes (i,t_i-l) to nodes (j,t_j+u). Capacity is determined by the type and number of aircraft used in the corresponding route for each arc.

Finally, consider all the nodes (i,t_p) and (i,t_q) where $t_p<t_q$. We add an uncapacitated arc from (i,t_p) to (i,t_q). These arcs correspond to "waiting" arcs for the requirements. A sample network is presented in Figure 3.6. It is constructed according to described process above for a 2-route, 3-origin, 5-destination, and 7-intermediary node system.

We have three requirements. The details of the requirements are provided in Table 3.2. The requirements are located at airfields 1, 3, and 5. All the requirements are released at time 0 and available for loading at time 1. Therefore the corresponding source nodes are (1,1), (3,1) and (5,1).

The destination nodes and latest delivery times of the requirements are also given in the figure. Therefore the destination nodes are (3,10), (4,10) and (1,10) respectively. Now, the problem is to assign requirements to the available routes while satisfying constraints. The solution is trivial for this example. We assign requirement 1 and 2 to route 1, and requirement 3 to route 2.

Table 3.2 Time-Phased Commodity and Passenger Deployment Table for Example Problem

No.	Origin	Destination	Release Time	Available Load Time	Latest Delivery Time	W (kg)	V (m^3)	Number of Passengers	Priority No.
1	1	3	0	1	10	2500	12	2	2
2	3	4	0	1	10	3200	16	3	1
3	5	1	0	1	10	4800	22	12	2

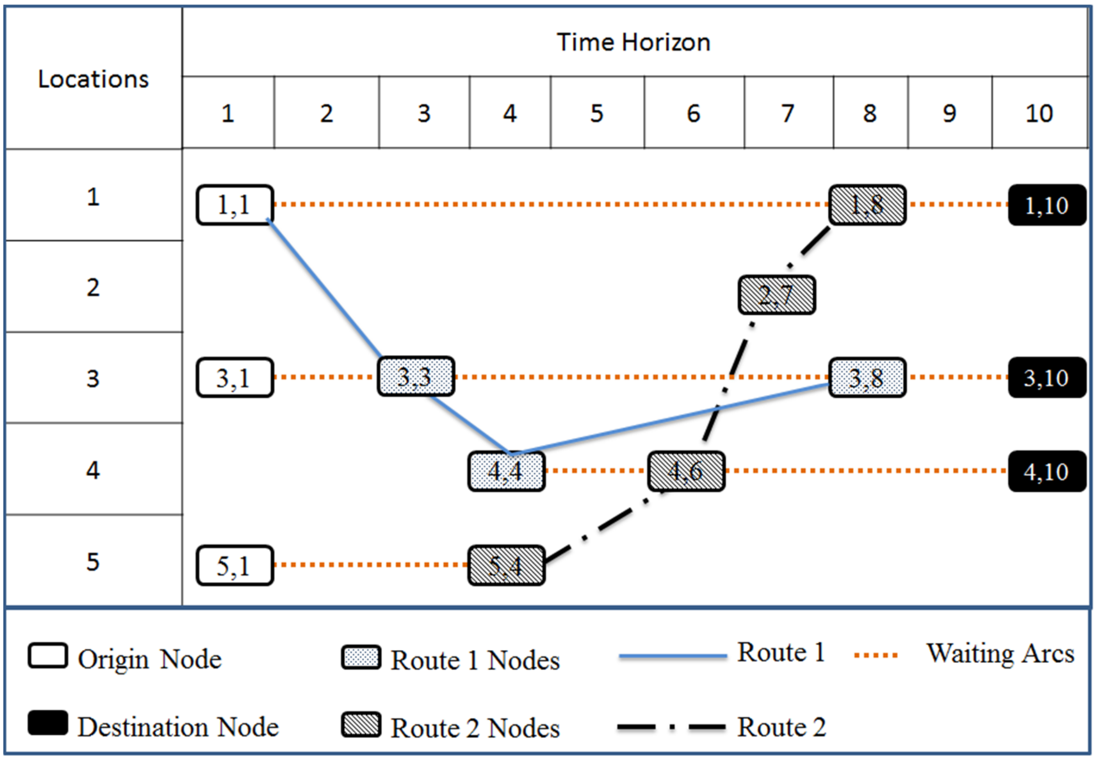

Figure 3.6 A Sample Time and Space Network Flow Diagram

Since service level parameters are determined for each priority class at the tactical level, they are implemented in the model as parameters. For each priority class, we have an associated service level and we impose the model to hold minimum service level requirements. For example priority number 1 is the most critical priority, and requires a 100% service level satisfaction. Therefore, all the commodities in this class should be scheduled for transportation here too.

Decision Variables

On the time and space network, we also represent our decisions by using the following decision variables that correspond to:

- Set of requirements scheduled for transportation
- Set of requirements scheduled on a route leg
- Number and type of aircraft scheduled for each route
- Volume / Passenger configuration of each aircraft on each route leg

Objective Function

Recall that the current system has multiple objectives while satisfying the system constraints. These objectives are minimization of costs and maximization of service levels for each priority class. However, we used minimization of cost as a single objective and service levels as a constraint of the mathematical model. The main reason for making this modification is the difficulty of expressing different "cost" units that have completely different scales. Assigning improper weights to two components of the objective function may result in misleading results, and determination of good weights is another difficulty to specify the tradeoff between cost and service level. The other difficulty of ACSM approach is setting minimum service level requirements. For class 1, we have a service level of 100% satisfaction as in the original model. We have diminishing service levels for other classes. Aircraft flight costs are calculated per flight hour based on direct costs which include fuel costs, maintenance costs, service costs, flight crew costs and depreciation costs and indirect costs which include indirect personnel costs, operating costs, management and support costs. In the next step total flight time is calculated by using the speed of corresponding aircraft type and distance of the route. Finally, total cost of corresponding route is calculated for each aircraft type by using the flight cost per hour and total flight hour. We sum cost figures associated with all route and aircraft combinations to obtain the total cost.

Flow Conservation Constraints

Flow conservation constraints for source nodes ensure the flow conservation in source nodes. For each source node i and requirement m pair, if requirement m is scheduled for transportation, only an outflow from node i is imposed.

Flow conservation constraints for destination nodes provide the flow conservation in destination nodes. For each destination node j and requirement m pair, if requirement m is scheduled for transportation, only an inflow to node j is imposed.

Flow conservation constraints for enroute nodes control the flow conservation in enroute nodes. For each intermediary node i and requirement m pair, if requirement m is scheduled for transportation, total inflow equal to total outflow.

Capacity Constraints

In the proposed model, in addition to scheduling problem, we also have a cargo loading problem. Each cargo requirement comes with specific weight and volume information. We pack these requirements on plates. Each plate has specific volume and weight carrying capacity. We need to fit all cargo requirements to plates. This problem is called bin packing problem in the literature and it is an NP-hard problem as explained in literature review chapter. Within the scope of this thesis, we don't consider this problem. Instead, we define a volume efficiency parameter for each aircraft type in order to handle realistic use of the plates without solving actual bin packing problems. This way it is nearly impossible to use all of the volume holding capacities of the plates.

In order to handle capacity limitations more realistically, we impose several capacity constraints in to the model. These constraints are weight, takeoff weight, volume, passenger, and plate capacities due to aircraft type.

First, each aircraft has a maximum weight carrying capacity. The total weight (weight of commodities and passengers) should be less than or equal to the corresponding weight carrying capacity of the aircraft. Here each passenger is assumed to be 110 kg with personnel belongings.
Second, takeoff weight capacity constraint is for representing the maximum weight of the aircraft before flight. We consider empty weight of the aircraft, total weight of fuel available, and total weight of commodities in this constraint. Therefore, we have two types of weight capacity constraints in total.

Third, we have volume capacity constraints. As we have explained before, passengers and cargo are carried together at the same area and the amount of commodities an aircraft can carry is based on the number of passengers and the amount of cargo where cargo is carried on plates. Each aircraft has a plate holding capacity for main cargo section while having a capacity of one plate for the rear ramp section. Main cargo section is for passenger and cargo transportation; however, rear ramp section can only be used for cargo transportation. Therefore, volume capacity can be expressed as a function of the number of plates and number of passengers. The number of plates used determines the configuration. To illustrate if one plate is used, than the volume capacity of the aircraft is the volume capacity of the used plate. Each aircraft has different plate holding capacities. Therefore, the number of volume capacity configurations is equal to the plate holding capacities of the aircraft.

Fourth, commodity based capacity constraint is defined as passenger capacity constraints. Similar to the volume capacity constraints, passenger capacity depends on the number of plates used. Since passengers and cargo are carried in the main cargo hold section of the aircraft, the available area is shared between passengers and plates. Therefore, as the number of plates increases, passenger carrying capacity decreases.

Finally, we have plate holding capacities for each aircraft. This constraint set defines the relation between volume and passenger capacity of the aircraft.

Route Conservation Constraints

This constraint set is used for controlling transshipments. We do not allow transshipments at all nodes. If a requirement arrives at node *i* on route *r* for a subset of intermediary nodes, it should depart from the node *i* on route *r*. We allow transshipments for other nodes, and thus the commodities can be transported on different nodes until arriving at their destinations.

Aircraft Supply Constraints

We have a set of aircraft available for each route *r*. This supply set may include different types and numbers of aircraft. The assignment is done according to available aircraft types and numbers.

Service Level Constraints

A predetermined service level should be satisfied for each priority class. It means that a percent of accepted requirements with priority *pr* should be greater than or equal to the corresponding service level of the priority class *pr*.

Next we give the mathematical formulation of ACSM. First, all sets, parameters, and decision variables are introduced. Second, the objective function and constraints are defined and explained in the next chapter.

CHAPTER 4

MATHEMATICAL FORMULATION OF THE ACSP

The following sections describe the sets, parameters, decision variables that are used in modeling, and present the mathematical formulation of the problem. The mathematical model is relatively complex and there are substantial details in presentation. However, a basic understanding is accessible by first examining the decision variables and then the constraints, referring to the data definitions as needed.

4.1 Sets and Parameters

Definition of the Sets

I	=	$\{i/i=1,\ldots\ldots\ldots\ldots\ldots,I\}$	Set of nodes in time and space network.
L	=	$\{l\,/\,l=1,\ldots\ldots\ldots\ldots\ldots,L\}$	Set of locations.
M	=	$\{m\,/\,m=1,\ldots\ldots\ldots\ldots,M\}$	Set of movement requirements.
R	=	$\{r\,/\,r=1,\ldots\ldots\ldots\ldots\ldots,R\}$	Set of routes.
A	=	$\{a\,/\,a=1,\ldots\ldots\ldots\ldots,A\}$	Set of aircraft types.
B	=	$\{b\,/\,b=1,\ldots\ldots\ldots\ldots,B\}$	Set of number of aircraft.
C	=	$\{c\,/\,c=1,\ldots\ldots\ldots\ldots,C\}$	Set of capacity configurations.
T	=	$\{t\,/\,t=1,\ldots\ldots\ldots\ldots\ldots,T\}$	Set of time periods.
ARC	=	$\{arc\,/\,arc=1,\ldots\ldots,ARC\}$	Set of all arcs between nodes.
PR	=	$\{pr\,/\,pr=1,\ldots,5\}$	Set of priorities.
$RARC$	=	$\{rarc\,/\,rarc=1,\ldots,RARC\}$	Set of route arcs.
$P(i)$			Set of predecessor arcs for node *i.*
$F(i)$			Set of successor arcs for node *i.*

Parameters for Movement Requirements

$Source_m$	Source node for requirement *m.*
$Dest_m$	Destination node for requirement *m.*

RT_m	Release time of requirement m.
ALT_m	Available load time for requirement m.
LDT_m	Latest delivery time for requirement m.
W_m	Weight of requirement m (in kilograms).
V_m	Volume of requirement m (in cubic meters)
P_m	Number of passengers in requirement m.
$PAXW$	Weight of a passenger including personal belongings.
$Prio_m$	Priority of requirement m.

Parameters for the Nodes

Loc_i	Corresponding airport of the node i.
T_i	Corresponding time point of the node i.

Parameters for Route and Aircraft Pairs

$WCAP_{ra}$	Weight capacity of route r and aircraft type a.
$WTakeoff_{ra}$	Takeoff weight capacity of route r and aircraft type a.
$Supply_{ar}$	Available supply of aircraft type a for route r.

Parameter for Aircraft and Arc Pairs

$Fuelweight_{ajk}$	Amount of fuel available on aircraft a before flying arc (j,k).

Parameters for Aircraft Types

$Voleff_a$	Volume efficiency factor for loading process of aircraft type a.
$PlCap_a$	Plate capacity of main cargo hold section of aircraft type a.

$VConf_{ac}$	Volume capacity of aircraft type a of configuration c.
$PConf_{ac}$	Passenger capacity of aircraft type a of configuration c.
$RampCap_a$	Volume capacity of ramp section of aircraft type a.

Parameters for the Cost Calculation

$Distance_{ln}$	Flight distance between airports l and n. (in nautical miles).
$Speed_a$	Average speed of aircraft a (in nautical miles/hour).
$Cost_a$	Cost of aircraft type a per hour.
$Rcost_{r,a}$	Cost of route r for aircraft type a.

We have considered direct and indirect costs for cost calculation,. As direct costs we included the fuel costs, maintenance costs, service costs, flight crew costs, and depreciation costs. As indirect costs, we have considered indirect personnel costs, operating costs, and management and support costs. The cost figures are based on per flight hour. If we multiply cost figure by time, we obtain the total cost of the corresponding arc. If we sum the arcs that correspond to a route, we obtain the total route cost as illustrated below.

$$\begin{aligned} Cost_a = {} & [Fuelcost_a + Maintenance_a + Service_a + Crew_a + Depreciation_a] + \\ & [Personnel_a + Operating_a + Management_a + Support_a] \end{aligned} \tag{4.1}$$

Cost of traversing from l to n by using aircraft a:

$$Arccost_{a,l,n} = \frac{Distance_{l,n}}{Speed_a} * Cost_a \tag{4.2}$$

Cost of the route for the aircraft type a:

$$RCost_{r,a} = \begin{array}{c} \sum_{l}\sum_{n} Arccost_{a,l,n} \\ for\ \forall\ (j,k) \in r \\ loc(j) = l\ and\ loc(k) = n \end{array} \tag{4.3}$$

Parameters Related with Service Level

$Serlevel_{pr}$	Service level percent of the priority *pr.*
Num_{pr}	Number of requirements that have priority *pr.*

4.2 Decision Variables, Objective Function and Constraints

Decision Variables

$$x_m = \begin{cases} 1 & if\ requirement\ m\ is\ scheduled\ for\ transportation. \\ 0 & otherwise. \end{cases}$$

$$y_{ma}^{jk} = \begin{cases} 1 & if\ requirement\ m \text{ is scheduled to aircraft } a \text{ on arc } (j,k). \\ 0 & otherwise. \end{cases}$$

z_{ra} = Number of aircraft of type a that are scheduled on route r

$$VC_{abc}^{jk} = \begin{cases} 1 & if\ b \text{ aircraft of type } a \text{ and volume configuration } c \\ & \qquad \text{are assigned on arc}(j,k) \\ 0 & otherwise \end{cases}$$

$$PC_{abc}^{jk} = \begin{cases} 1 & if\ b \text{ aircraft of type } a \text{ and passenger configuration} \\ & \qquad c \text{ are assigned on arc}(j,k) \\ 0, & otherwise \end{cases}$$

Objective Function

Our objective is the minimization of total cost. As explained before aircraft flight costs are calculated per flight hour based on direct costs which include fuel costs, maintenance costs, service costs, flight crew costs, and depreciation costs and indirect costs which include indirect personnel costs, operating costs, management, and support costs. In the next step, total flight time is calculated by using the speed of corresponding aircraft type and distance of the route. Finally, total cost of corresponding route is calculated for each aircraft type by using the flight cost per hour and total flight hour. The route cost is incurred if the aircraft is assigned to the route. We obtain the total cost by summing over all route and aircraft combinations as illustrated below.

$$\sum_{r}\sum_{a} Rcost_{ra} z_{ra} \tag{4.4}$$

Flow Conservation Constraints for Source Nodes

This constraint set ensures the flow conservation in source nodes. Total outflow from node i minus total inflow to node i is equal to x_m for each source node and requirement pair. It means that if a movement requirement is accepted, then x_m=1. So, an outflow from source node is imposed.

$$\sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in F(i)}} y_{ma}^{jk} - \sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in P(i)}} y_{ma}^{jk} = x_m \tag{4.5}$$

$for\ \forall\ (i,m) \in s(i,m).$

Flow Conservation Constraints for Destination Nodes

This constraint set ensures the flow conservation in destination nodes. Total outflow from node i minus total inflow to node i is equal to $-x_m$ for each destination node and requirement pair. It means that if movement requirement is accepted, then x_m=1. So, an inflow to destination node is imposed.

$$\sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in F(i)}} y_{ma}^{jk} - \sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in P(i)}} y_{ma}^{jk} = -x_m \tag{4.6}$$

$for\ \forall\ (i,m) \in d(i,m).$

Flow Conservation Constraints for Enroute Nodes

This constraint set ensures the flow conservation in enroute nodes. Total outflow from node i minus total inflow to node i is equal to 0 for each enroute node and requirement pair. It means that the total inflow is equal to the total outflow in enroute nodes.

$$\sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in F(i)}} y_{ma}^{jk} - \sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in P(i)}} y_{ma}^{jk} = 0 \tag{4.7}$$

$for\ \forall\ (i,m) \notin d(i,m) and\ \ \notin s(i,m).$

Weight Capacity Constraints

This constraint set limits the weight capacity on each route arc, which depends on type of the aircraft assigned. Total weight is the sum of weights of the movement requirements and passengers that are assigned to the corresponding arc and aircraft pair. Right hand side of the constraint is the sum of weight capacity of the assigned aircraft.

$$\sum_{m} (W_m + p_m\ PaxW\ ) y_{ma}^{jk} \leq WCap_{ra} z_{ra} \tag{4.8}$$

$$for\ \forall\ \ a\ and\ (j,k) \in Rarc.$$

Takeoff Weight Capacity Constraints

This constraint set limits the takeoff weight capacity on each route arc for the assigned aircraft types. In this constraint we consider the takeoff capacity for each aircraft type, which depends on the amount of cargo and passengers carried, fuel weight and weight of the aircraft. The total weight is the sum of weights of the movement requirements and passengers that are assigned to the corresponding arc and aircraft pair. Right hand side of the constraint is the capacity available for carrying cargo, which is defined as takeoff weight minus fuel weight if the aircraft type *a* is used on route *r*.

$$\sum_{m} (W_m + p_m\ PaxW\ ) y_{ma}^{jk} \leq (WTakeoff_{ra} - Fuelw_a^{jk})\ z_{ra} \tag{4.9}$$

$$for\ \forall\ (j,k) \in Rarc, a, and\ r.$$

The difficulty in this constraint is determination of available fuel weight on each arc. For that purpose, we assumed an average rate of fuel consumption obtained from historical reports according to aircraft type. We determined total fuel available in the aircraft by considering the distance of the route legs, average fuel consumption of the aircraft on that leg, and fuel capacity of the aircraft for each aircraft and route pair. By analyzing this data, we also determined refueling airports for the aircraft and route pairs.

Volume Capacity Constraints

This constraint set limits the volume capacity on each route arc for the assigned aircraft types. Total volume is the sum of volumes of the movement requirements that are carried on arc under consideration. $Vconf_{ac}$ corresponds to the volume capacity of the main cargo hold section of aircraft in configuration *c*. $RampCap_a$ corresponds to the volume capacity of ramp section of aircraft of type *a*. Finally, we multiply total volume capacity of the aircraft by a parameter $Voleff_a$ in order to handle the loading efficiency.

$$\sum_{m} V_m y_{ma}^{jk} \leq \left[\sum_{b} \sum_{c} (\ Vconf_{ac}\ VC_{abc}^{jk}\ ) + RampCap_a\ z_{ra} \right] Voleff_a \tag{4.10}$$

$for\ \forall\ \ (j,k) \in Rarc, a, and\ r.$

An aircraft can have only one type of volume configuration on a route arc at a time. Therefore, we have to limit number of configurations to one. Constraint 4.11 is used for this purpose.

$$\sum_{c} VC_{abc}^{jk} \leq 1 \tag{4.11}$$

$for\ \forall\ \ a, b\ and\ (j,k) \in Rarc.$

Finally, the total number of configurations on a route arc is equal to the total number of aircraft of type *a* assigned to the corresponding route.

$$\sum_{b} \sum_{c} VC_{abc}^{jk} = z_{ra} \tag{4.12}$$

$for\ \forall\ \ a, r\ and\ (j,k) \in r$

Passenger Capacity Constraints

Passenger capacity constraints are similar to volume capacity constraints. This constraint set limits the passenger capacity on each route arc for the assigned aircraft types. Total number of passengers on a route arc is the sum of the passengers in movement requirements that are carried on the arc under consideration. $Pconf_{ac}$ is the corresponding passenger capacity of aircraft type *a* in configuration *c*.

$$\sum_{c} P_m y_{ma}^{jk} \leq \sum_{b} \sum_{c} Pconf_{ac} PC_{abc}^{jk} \tag{4.13}$$

$for\ \forall\ \ (j,k) \in Rarc, a, and\ r.$

An aircraft can have only one type of passenger configuration on a route arc at a time. Therefore, we have to limit number of configurations to one. Constraint 4.14 is used for this purpose.

$$\sum_{c} PC_{abc}^{jk} \leq 1 \tag{4.14}$$

$for\ \forall\ \ a, b\ and\ (j,k) \in Rarc$

Finally total number of passenger configurations on a route arc is equal to the total number of aircraft of type *a* assigned to the corresponding route.

$$\sum_{b}\sum_{c} PC^{jk}_{abc} = z_{ra} \tag{4.15}$$

$$for\ \forall\ \ a, r\ and\ (j,k) \in r$$

Plate Capacity Constraints

As explained in Chapter 3, plate capacity depends on the volume and passenger configuration of the aircraft. This relation is formulated as in 4.16. Plate capacity of a route arc for the assigned aircraft depends on the number of aircraft type *a* assigned and the corresponding plate capacity of the aircraft. This sum should be greater than or equal to the total number of passenger and volume configurations multiplied by *(c-1)*. Here, we multiply by *(c-1)* because both passenger configuration *c* require *(c-1)* plate locations and cargo configuration *c* requires *(c-1)* plates.

$$\sum_{b}\sum_{c}^{c_a}\left[(c-1)\left(PC^{jk}_{abc} + VC^{jk}_{abc}\right)\right] \leq PLCap_a z_{ra} \tag{4.16}$$

$$for\ \forall\ \ a, r\ and\ (j,k) \in r$$

Route Conservation Constraints

This constraint set ensures that if a requirement arrives at node *i* on route *r*, it should leave the node on an arc that is also on route *r* for a subset of nodes. It means that transshipment is not allowed for all of the nodes. Only some nodes have transshipment capability.

$$\sum_{\substack{j \\ (j,k) \in B(i) \cap Rarc \\ (j,k) \in Rarc}}\sum_{k} y^{jk}_{ma} + \sum_{\substack{j \\ (j,k) \in F(i) \cap Rarc \\ (j,k) \notin Rarc}}\sum_{k} y^{jk}_{ma} \leq x_m \tag{4.17}$$

$$for\ \forall\ \ i \in i', r\ and\ m$$

Aircraft Supply Constraints

Number of aircraft assigned on route *r* should be less than or equal to the supply of aircraft type *a* on corresponding route.

$$z_{ra} \leq Supply_{ar} \tag{4.18}$$

$$for\ \forall\ \ a\ and\ r$$

Service Level Constraints

For each priority, a predetermined service level should be satisfied. It means that total number of accepted requirements that have priority *pr* should be greater than or equal to the corresponding service level times the number of requirements that have priority *pr*.

$$\sum_{\substack{m \\ Prio_m = pr}} x_m \geq Serlevel_{pr} Num_{pr} \text{ for } \forall \text{ pr} \tag{4.19}$$

Integrality Constraints

The decision variables *x, y, VC* and *PC* are binary variables and *z* is an integer variable.

$$x_m , y_{ma}^{jk} , VC_{abc}^{jk}, and\ PC_{abc}^{jk} \in \{0,1\} \tag{4.20}$$

$$z_{ra}\ is\ integer \tag{4.21}$$

The mathematical expressions explained in this chapter are summarized in Appendix A.

CHAPTER 5

COMPUTATIONAL RESULTS

We have constructed Air Cargo Scheduling Model (ACSM) in order to solve air cargo scheduling problem in Chapter 4. The model is implemented with General Algebraic Modeling System (GAMS) Build 23.5.1 and solved with CPLEX 12.2.0.0 on a computer having Windows 7 operating system with Intel® Core ™ 2.40 GHz i3 CPU and 3.00 GB of RAM. Model formulation produced in GAMS is given in Appendix B. Iterative Scheduling Methodology (ISM) is used for solving air cargo scheduling problem in the current system. The details of ISM are explained in section 3.1.

In this first part of the computational experiments, using real data taken from the current system, performances of two approaches, ACSM and ISM, are compared in terms of quality of the solutions produced. In the second part, we generate new test instances derived from real data in order to assess the performance of ACSM in detail. In the third part, we concentrate on disruptions that occur when the weekly schedule is running and analyze how the system responds to remove or lessen these disruptions.

5.1 Comparison of ISM with ACSM

For comparing ISM with ACSM on a set of test instances coming from real data, we use 5 data sets taken from the company that cover 5 consecutive weeks. Unfortunately, details of the data will not be presented here because of confidentiality of the data set. Some important features of these instances such as total weight, total volume, and total number of passengers to be carried are given in Table 5.1.

Table 5.1 Summary for the Test Instances

Instance Number	Number of Requirements	Total Weight (kg)	Total Volume (m^3)	Total Number of Passengers
1	148	50,061	111.25	336
2	147	49,748	110.55	343
3	150	48,057	106.79	331
4	156	49,183	109.30	246
5	150	47,136	104.75	271

For the system under consideration, the set of accepted requirements, assignment of aircraft to routes, and assignment of the requirements to routes are known from past reports. In order to compare the result of proposed model with the actual realization, we will consider two cases. In the first case, we use the same set of aircraft as realized in the system. In the second case, we let the model find the aircraft types to be used on each route.

First Case: Same set of aircraft used

We enforce the model to assign the same aircraft to the associated routes as implemented in practice. Our aim is to compare the service levels of our solution with the real situation. Note that because we used same aircraft in the routes, the costs are equal for ACSM and ISM. The service levels in terms of the percent of weight and volume of cargo and the percent of the number of passengers carried by ISM are provided in Table 5.2. All these measures are 100% for the results of ACSM for all instances.

Table 5.2 Service Levels for ISM

Instance Number	Weight (%)	Volume (%)	Passenger (%)
1	90.67	85.55	97.62
2	86.16	77.00	98.25
3	90.81	85.00	98.49
4	94.07	90.80	100.00
5	94.06	90.30	100.00

Note: All of the rates are 100 % for ACSM

As can be seen from the Table 5.2, ACSM provides better results in terms of the percent of commodities carried. All requirements are scheduled for transportation and 100% service level is achieved for all priority levels. However, ISM does not serve some requirements with low priority, large weight, large volume and large number of passengers. There may be several reasons for that difference between two approaches. In order to determine the main reason we consider two main factors.

It should be noted that it is nearly impossible to use the entire volume holding capacity of the plates in practice. The realized loading efficiency becomes an important factor in this sense that shows effectiveness in use of available volume capacity. We decided to play with the loading efficiency of the plates in order to make a fair comparison. A volume efficiency parameter is introduced for each aircraft type. We rerun ACSM by decreasing the volume efficiency parameter at each step until a significant change in resulting service levels is observed. Although this level of services changes from case to case, on average service levels in ACSM didn't change until volume efficiency becomes equal to 60%. Thus, we conclude that volume efficiency is not the main reason of the differences in service levels and we decided to test the impact of transshipment on the results.

By transshipment we mean the exchange of cargo and passengers between routes and aircraft. As explained before, ACSM allows transshipments at some airports. The model output reveals that 94% of requirements are sent to the customers directly at the best solution. However, even if we restrict transshipment, all requirements are transported and 100% service level is achieved again. So we conclude that ACSM explores all possible solutions and finds the best solution whereas ISM is based on the experience of operators.

Second Case: Let model decide aircraft to be used

The first case indicates possible improvements in terms of service levels when the problem is solved as an optimization problem. However, constraining use of the same aircrafts on the same routes does not allow further reductions in total cost figures even if possible. In the second case, we let the model choose aircraft from available aircraft fleet for arranging the routes, using the same test instances used for the first case. Aircraft assignments for ISM and ACSM are presented in Table 5.3 and Table 5.4, respectively. We have 5 routes; each has different time frame and set of airports available for aircraft assignment. Besides we have 3 types of aircraft, each has specific properties in terms of cost and capacity. In these tables we illustrate the types of aircraft assigned to each route and corresponding total costs of these assignments.

Table 5.3 Scheduled Aircraft and Total Costs for ISM

Instance Number	Route Number					Total Cost (৳)
	1	2	3	4	5	
1	C130 CN235	C130 CN235	C130	C160	CN235	211,496
2	C160 CN235	C160 CN235	C160 CN235	C160 CN235	CN235	162,002
3	C130	C130	C130	C130	CN235	183,270
4	C160	C160	C160	C160	CN235	106,097
5	C130	C130	C160	C160	CN235	145,030

As seen from Table 5.3, we observe that two aircrafts are assigned for some routes for ISM. Also, C130 type aircraft is preferred to C160 despite the fact that C160 has lower cost. ISM prefers C130 possibly because it has larger weight carrying capacity compared to C160.

Table 5.4 Scheduled Aircraft and Total Cost for ACSM

Instance Number	Route Number					Total Cost (৳)
	1	2	3	4	5	
1	C160	C160	C160	C160	CN235	106,097
2	C160	C160	C160 CN235	C160 CN235	CN235	133,776
3	C160	C160	C160	C160	CN235	106,097
4	C160	C160	C160	C160	CN235	106,097
5	C160	C160	C160	C160	CN235	106,097

As seen from Table 5.4, except route 3 and 4 of instance 2, one type of aircraft is assigned on each route at the solution of ASCM and C160 is preferred to C130 as it has lower costs. For instance 2 we see from Table 5.3 that ISM assigns two aircrafts for routes 1 to 4. However ACSM assigns two aircrafts only for route 3 and 4. Among all of the 5 instances, the number of passengers is the highest in instance 2. Therefore the capacity constraints cannot be satisfied for one type of aircrafts in route 3 and 4. Therefore second aircraft is scheduled for these routes. Comparison of the results of ISM and

ACSM in terms of cost figures is presented in Figure 5.1. As can be seen from this figure, the total cost incurred in ACSM is always less than or equal to the total cost incurred in ISM for all test instances.

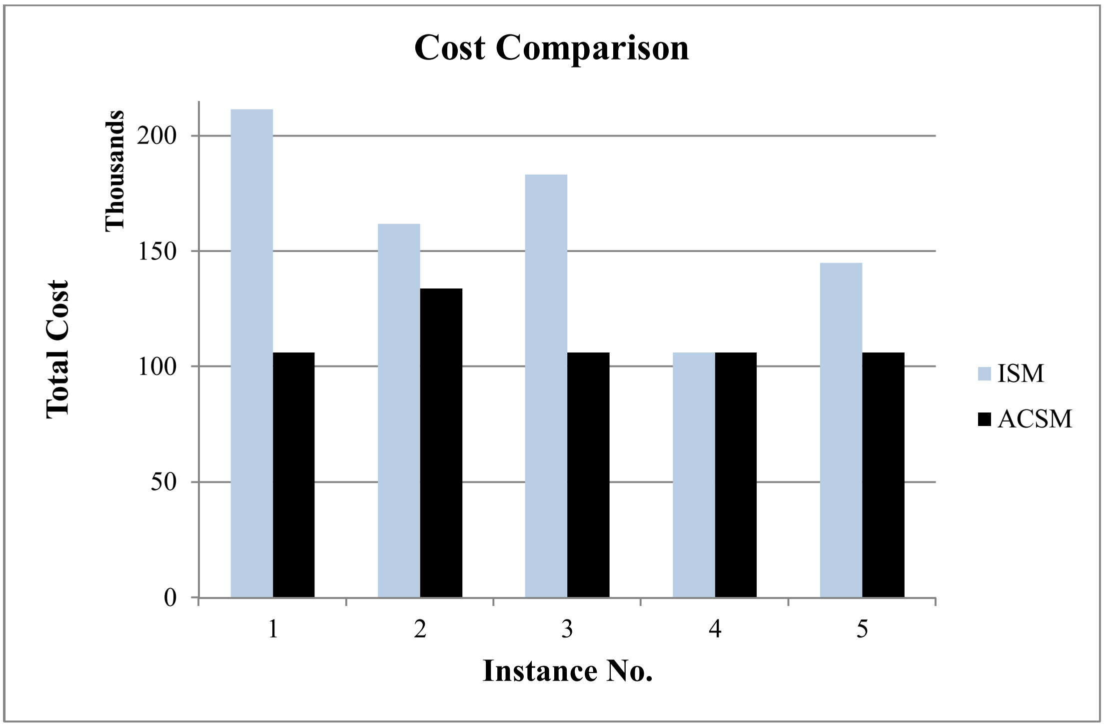

Figure 5.1 Cost Comparison of ISM and ACSM

Another comparison can be made in terms of solution times. In order to come up with a solution by using ISM, two experienced personnel works one working day (16 man-hour in total) and usually the produced solution requires some modifications during the week. On the other hand, in order to solve the problem by using ACSM, on average we need one hour in total for constructing the network for the model, updating the parameters and running the model. After construction of the network, the MIP model can be solved within seconds by using a standard solver. Results obtained for all test instances are provided in the Table 5.5. As can be seen from the table, ACSM solves the problem within 7 seconds on average.

5.2 Experimental Results for Generated Test Instances

In section 5.1, we used test instances based on the real data. However, in order to conduct further analysis and evaluate performance of ACSM, we have created new test instances. In the first experiment, we test the tightness of ACSM on a new test instance. Details of this instance are provided in Appendix C. In the second experiment, we generate new instances by using the first week of the real data as base instance.

Table 5.5 Selective Statistics for ACSM

Instance Number	Number of Requirements	Number of Binary Variables	Number of Iterations	CPU Time (seconds)
1	148	85,681	2,597	5.4
2	148	85,681	3,094	5.7
3	150	86,739	2,278	5.4
4	156	89,913	3,241	6.9
5	150	86,739	3,714	6.9

Experiment 1

We start with an initial movement requirement set and increase the weight and volume of the cargo and number of passengers by 5% iteratively and observe the chances in the service levels of priority classes and CPU times while using the same set of aircrafts for each instance. The results of the experiment are presented in Table 5.6. In this table, we start with the base instance 1 and run the ACSM and obtain the service level statistics and CPU times. For the second instance we increase the weight, volume and number of passengers in each requirement of instance 1 by 5% and run the model again and obtain the service levels and CPU times for instance 2. We continue in this manner until instance 5, in which we increase the weight, volume and number of passengers by 20% of the instance 1. As can be seen from the table, we observe a decrease in service level in instance 3. And after this instance the service level continues to decrease for instance 4 and 5. The main reason for this decrease in service level is the capacity of the aircrafts. As we increase the cargo and passenger to be carried while using the same set of aircrafts, the model eliminates some of the requirements and correspondingly the service level decreases for some of the priority classes.

Another conclusion that can be deducted from this experiment is the increase in CPU times. As the amount of cargo increased, the capacity constraints become tighter and as a result the number of iterations increases. Therefore CPU times increases.

Table 5.6 Service Level Statistics and CPU Times for Generated Test Instance

Instance No.	Service Levels for Priority Classes (%)					CPU Time (Seconds)
	1	2	3	4	5	
1	100	95	90	85	80	5.7
2	100	95	90	85	80	6.8
3	100	95	85	80	80	13.5
4	100	95	80	75	70	22.3
5	100	90	80	75	70	35.8

Experiment 2

In order to create new instances, we used the first week of the real data as base case. We multiplied the weight and volume of the cargo, and the number of passengers in each requirement by 2 in order to obtain instance 2, by 3 in order to obtain instance 3 and so on. The results are illustrated in Table 5.7. As can be seen from the table, CPU times increases as we increase the amount of cargo and passenger to be scheduled. This is because as amount of cargo increases, the capacity becomes tighter and in order to arrive at a solution the model executes more iterations and correspondingly CPU times increases.

Table 5.7 Selective Statistics, Number of Iterations, and CPU Times for Experiment 2

Instance No.	Weight (kg)	Volume (m^3)	Number of Passenger	Number of Iterations	CPU Time (seconds)
1	50,061	111.25	336	2,117	5.4
2	100,122	222.51	672	7,665	13.8
3	150,183	333.75	1,008	19,101	36.1
4	200,244	445.01	1,344	35,995	92.9
5	250,305	556.25	1,680	47,086	143.1

5.3 Alternative Scenario Analysis

Up to now we have assumed that all of the transportation requirements are known and submitted to the system before the planning process begins. In other words, planning process is done under perfect information and we have all of the transportation requirements, their corresponding attributes, etc. However in reality some disruptions may occur during the week. For example, some of the movement requirements may be cancelled or some urgent requirements with high priorities may occur during the implementation of weekly plans. To test the effects of such changes (or to incorporate the uncertainties in the nature of demand process) we design a scenario where new orders or cancelation occurs during the week and disrupts the implementation plans prepared in the beginning of the week. In order to handle this situation the schedule should be updated and new requirements should be included in the updated transportation plan according to their priorities. Such situations may incur extra costs or effectiveness of available capacity usage may decrease, etc. in order to satisfy service level constraints. Some new aircraft may be included in the updated schedule. To handle this situation we propose following procedure:

a. Prepare the schedule by considering all available movement requirements.

b. Assume new requirements arrive at time *t*. Determine the set of requirements that have been transported up to time *t*.

c. Remove these requirements from the time phased movement requirement list and add the newly arrived requirements to the list.

d. Update the model parameters for the new list.

e. Run the model and obtain the new schedule.

In order to observe the effect of disruption, we assume that we have 100 movement requirements initially that have different priorities and delivery time windows. We use the ACSM in order to create schedule for these 100 requirements. The produced schedule is as in Table 5.8 schedule 1.In the middle of the week (Wednesday) another 48 movement requirements are submitted. We determine the requirements already transported on route 1 (on Monday) and on route 2 (on Tuesday) and remove these requirements from the list. There are 38 requirements already transported and 62 requirements are waiting to be transported. Therefore, in the updated list we have 62+48=110 requirements and we have routes 3, 4 and 5 available for scheduling. We run the model for these 110 requirements and 3 available routes and obtain schedule 2 in Table 5.8. On Thursday, another 38 requirements are submitted. We determine the requirements already transported on route 1 (on Monday), on route 2 (on Tuesday), and on route 3 (on Thursday) and remove these requirements from the list. There are 80 requirements already transported and 68 requirements are waiting to be transported. This time we have routes 4 and 5 available for scheduling. We run the model once more for the remaining requirements and obtain schedule 3 of the Table 5.8. The combination of first three schedules is also illustrated in Table 5.8. For Monday and Tuesday we use set of aircraft obtained by schedule 1, for Thursday we use set of aircraft obtained by schedule 2, and for Friday we use set of aircraft obtained schedule 3. As a result total cost of this combination schedule is 129,041 ₺. If all of the requirements are submitted before the planning week the total cost would be 106,097 ₺. Therefore total cost can be reduced up to 20% for this example if all requirements are submitted on time.

Table 5.8 Scheduled Aircraft and Total Cost for ACSM

Schedule No.	**Route No.**					**Total Cost (₺)**
	1	**2**	**3**	**4**	**5**	
1	C160	C160	CN235	CN235		77,155
2			C160	C160	CN235	56,621
3				C130	CN235	60,151
1+2+3	C160	C160	C160	C130	CN235	129,041
4	C160	C160	C160	C160	CN235	106,097

As a result, if all of the requirements are submitted before the planning period, total cost can be minimized further. Requirements submitted during the week may result in extra costs as illustrated in the example above.

CHAPTER 6

CONCLUSIONS AND DIRECTIONS FOR FURTHER STUDY

In this thesis, we study the Air Cargo Scheduling Problem (ACSP) that is based on a real life application. The objective is to move cargo and passengers based on a weekly flight schedule from a number of origin airports to destination airports by means of a transportation system that has predefined carrier routes, flight schedules and a fleet of aircraft with different characteristics. The system under consideration has specific characteristics. Unfortunately, related studies in the literature do not cover all aspects of the problem alone. The problem can be expressed as a combination of several problem types such as vehicle routing problem, container/liner shipping problem, air cargo network planning problem, and the three-dimensional bin packing problem.

The current system, its entities, the relationship between entities, and the decision processes are introduced. In order to improve current process, ACSM that is based on mixed integer programming is proposed. The model is based on the time and space network that mimics events during decision process. The model is tested with the real data and the results are compared with the current methodology under different scenarios. The performance of the model is also tested with generated test problems derived from real data. The ACSM produced better results compared to Iterative Scheduling Methodology (ISM) in a short amount of time.

In this study we approximate some aspects of the real system. For instance, we used average values obtained from historical reports and statistics to approximate flight costs. However, in reality, flight costs depends on many factors such as total weight on the aircraft, the number of takeoffs and landings on a route, altitude of flight, meteorological and atmospheric conditions like wind speed, pressure, and so on. In order to calculate more realistic flight costs, a more comprehensive cost approximation methodology can be studied.

The second major approximation is used for loading aircraft. Recall that, commodities in different dimensions should be packed into a number of plates in different dimensions depending on aircraft type. This requires solving a Three-Dimensional Bin Packing Problem (3D-BPP) for each aircraft before departing from each airport. Because of the fact that 3D-BPP is strongly NP-hard, to solve a bin packing problem for each route leg would increase complexity and solution times of the model extensively. As a future research, the loading process can be handled by a similar approach as in the 3D-BPP to represent the real system better.

In this study, we considered only the operational aspects of the air cargo scheduling problem. Although reducing the costs and improving the service quality at the operational level are important, more reductions and higher improvements might be possible when tactical level decisions (e.g. determination of routes and their frequencies) and strategic level decisions (e.g. determination of fleet size and mix) are considered. For instance, instead of fixed routes, a dynamic routing approach may be used. In this case we can not only decrease transportation costs, but also handle seasonality in transportation requirements. Therefore, a future research might be to apply a holistic approach that incorporates the course of actions from different decision levels in order to reach a cost effective and more responsive cargo system.

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APPENDIX A

MATHEMATICAL MODEL

Minimize

$$\sum_{r}\sum_{a} Rcost_{ra} z_{ra} \tag{A.1}$$

Subject to

$$\sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in F(i)}} y_{ma}^{jk} - \sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in P(i)}} y_{ma}^{jk} = x_m \tag{A.2}$$

$for\ \forall\ (i,m) \in s(i,m).$

$$\sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in F(i)}} y_{ma}^{jk} - \sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in P(i)}} y_{ma}^{jk} = -x_m \tag{A.3}$$

$for\ \forall\ (i,m) \in d(i,m).$

$$\sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in F(i)}} y_{ma}^{jk} - \sum_{a}\sum_{j}\sum_{\substack{k \\ (j,k)\in P(i)}} y_{ma}^{jk} = 0 \tag{A.4}$$

$for\ \forall\ (i,m) \notin d(i,m) and\ \ \notin s(i,m).$

$$\sum_{m}(W_m + p_m\ PaxW\ )y_{ma}^{jk} \leq WCap_{ra} z_{ra} \tag{A.5}$$

$for\ \forall\ \ a\ and\ (j,k) \in Rarc.$

$$\sum_{m}(W_m + p_m\ PaxW\ )y_{ma}^{jk} \leq (WTakeoff_{ra} - Fuelw_{a}^{jk})\ z_{ra} \tag{A.6}$$

$for\ \forall\ (j,k) \in Rarc, a, and\ r.$

$$\sum_m V_m y_{ma}^{jk} \leq \left[\sum_b \sum_c (Vconf_{ac}\, VC_{abc}^{jk}) + RampCap_a\, z_{ra}\right] Voleff_a \qquad (A.7)$$

$for\ \forall\ \ (j,k) \in Rarc, a, and\ r.$

$$\sum_c VC_{abc}^{jk} \ \leq 1 \qquad (A.8)$$

$for\ \forall\ \ a, b\ and\ (j,k) \in Rarc.$

$$\sum_b \sum_c VC_{abc}^{jk} \ = z_{ra} \qquad (A.9)$$

$for\ \forall\ \ a, r\ and\ (j,k) \in r$

$$\sum_c P_m y_{ma}^{jk} \ \leq \sum_b \sum_c Pconf_{ac} PC_{abc}^{jk} \qquad (A.10)$$

$for\ \forall\ \ (j,k) \in Rarc, a, and\ r.$

$$\sum_c PC_{abc}^{jk} \ \leq 1 \qquad (A.11)$$

$for\ \forall\ \ a, b\ and\ (j,k) \in Rarc$

$$\sum_b \sum_c PC_{abc}^{jk} \ = z_{ra} \qquad (A.12)$$

$for\ \forall\ \ a, r\ and\ (j,k) \in r$

$$\sum_b \sum_c^{c_a} \left[(c-1)(PC_{abc}^{jk} + VC_{abc}^{jk})\right] \ \leq PLCap_a z_{ra} \qquad (A.13)$$

$for\ \forall\ \ a, r\ and\ (j,k) \in r$

$$\sum_{\substack{j \\ (j,k) \in B(i) \cap Rarc \\ (j,k) \in Rarc}} \sum_{k} y_{ma}^{jk} + \sum_{\substack{j \\ (j,k) \in F(i) \cap Rarc \\ (j,k) \notin Rarc}} \sum_{k} y_{ma}^{jk} \leq x_m \qquad A.14)$$

$for\ \forall\ i \in i', r\ and\ m$

$$z_{ra} \leq Supply_{ar} \qquad (A.15)$$

$for\ \forall\ a\ and\ r$

$$\sum_{\substack{m \\ Prio_m = pr}} x_m \geq Serlevel_{pr} Num_{pr} \text{for } \forall \text{ pr} \qquad (A.16)$$

$$x_m, y_{ma}^{jk}, VC_{abc}^{jk}, and\ PC_{abc}^{jk} \in \{0,1\} \qquad (A.17)$$

$$z_{ra}\ is\ integer \qquad (A.18)$$

APPENDIX B

GAMS FORMULATION OF ACSM

* Air Cargo Scheduling Problem
* Thesis by : Yavuz DURDAK
* Middle East Technical University Industrial Engineering Department

SETS

I	Set of nodes in the network /1*148/
M	Set of movement requirements /1*148/
L	Set of airports /1*13/
R	Set of routes /1*3/
A	Set of aircraft types /c130, c160, cn235/
B	Set of number of aircraft type used on one of the routes /1*5/
C	Capacity configurations for aircrafts /1*6/
REQLABEL	Set of movement requirement table labels /Ori, Dest, ALT, LDT, Wload, Vload, Pax, Prio/
ROUTELABEL	Set of route table labels /WCAP,VCAP,PAXCAP,WTakeoff / ;
ALIAS(i,j,k);	
ALIAS (l,n);	
PR	Set of priorities of movement requirements /1*5/
PRIO(m,pr)	Set of priorities of each movement requirement m /1.1, 2.1, 3.3, 4.4, .../
S(i,m)	Set of source nodes i for movement requirements m /6.1, 10.2, 10.3, 10.4, ... /
D(i,m)	Set of destinations i for movement requirements m /68.1, 67.2, 96.3, 93.4, ... /
LOCIL(i,l)	Corresponding airport l of node i /1.1, 2.2, 3.3,. . . . . . /
ARC(j,k)	Set of all arcs in the network /1.18, 2.20, 3.19, 4.25, ... /

RARCS(j,k)	Set of arcs that corresponds to a route leg /14.15, 15.16, 16.17, 17.18, .../
P(i,j,k)	Predecessor arcs (j,k) of node i /14.8.14, 15.(10.15,14.15), 16.(12.16,15.16), .../
F(i,j,k)	Successor arcs (j,k) of node i /1.1.18, 2.2.20, 3.3.19, ... /
FUELARCS(a,j,k)	Route arcs and aircraft type mapping / (c130, c160, cn235).(14.15, 15.16, 16.17, ...) /
ROUTEARC(r,j,k)	Route and route arcs mapping /1.14.15, 1.15.16, 1.16.17, 1.17.18, ... /
ROUTEAIRCRAFT(a,r,j,k)	Aircraft, route and route arcs mapping /(c130, c160, cn235).(1.14.15, 1.15.16, .../

PARAMETERS

TABLE *REQDATA(m,reqlabel)* Time phased movement requirement table

	Ori	Dest	ALT	LDT	Wload	Vload	Pax	Prio
1	6	10	0	44	0	0.0000	20	1
2	10	9	0	44	1100	2.4444	1	1
3	10	5	0	90	300	0.6667	0	3
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.

TABLE *ROUTEDATA (r,a,routelabel)* Capacities of route and aircraft mappings

	WCAP	VCAP	PAXCAP	WTakeoff
1.C130	20000	83	90	26900
1.C160	16000	83	89	22000
1.CN235	5950	34	48	6700
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

TABLE *FUELWEIGHT (a,j,k)* Total fuel consumption on arcs for aircraft types

	14.15	15.16	16.17	17.18	.	.
c130	8288	6697	5365	3848	.	.
c160	5124	4116	3297	2352	.	.
cn235	1813	1456	1162	826	.	.

TABLE *ARCCOST (a,l,n)* Variable cost of arcs according to aircraft types

	1	2	3	4	.	.	.	.
C130.1	0	3997	2918	18820	.	.	.	.
C130.2	3997	0	2568	19607	.	.	.	.
C130.3	2918	2568	0	19724	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.

SUPPLY (a,r)	Number of aircrafts available for route r /c130.1 1, c130.2 1, c160.1 1, c160.2 1, cn235.1 1, cn235.2 1, cn235.3 2/
RCOST (r,a)	Total flight cost in TL per hour for aircraft type a on route r;
RCOST (r,a) =	Sum((j,k)$Routearc(r,j,k), (Sum((l,n)$(locjl(j,l) and lockn(k,n)),Arccost(a,l,n))));
PLATECAP (a)	Plate capacity of aircraft type a /C130 5,C160 5,CN235 3/ ;
PAXW	Pax weight in kg /110/
SERLEVEL (pr)	Service levels for priority classes pr /1 1, 2 1, 3 1, 4 1, 5 1/;
NUMPR (pr)	Number of requirements that have priority pr /1 29, 2 35, 3 28, 4 19, 5 37/;
VOLEFF	Volume efficiency factor /0.90/;

VARIABLES

X(m)	1 if requirement m is carried via one of the routes
Y(m,a,j,k)	1 if requirement m is carried by aircraft type a on arc (j,k)
Z(r,a)	Number of type a aircrafts used for route r
PC(r,j,k,a,c,b)	1 if pax capacity of aircraft type a and number b on arc (j,k) of route r is configuration c
VC(r,j,k,a,c,b)	1 if Volume capacity of aircraft type a and number b on arc (j,k) of route r is configuration c
SL(pr)	Service level percent of priority pr
WT(j,k)	Total weight carried on arc (j,k)
WTA(a,j,k)	Total weight carried on arc (j,k) by aircraft type a on route r
PT(a,j,k)	Total weight carried on arc (j,k) by aircraft type a on route r

PLT(a,j,k)	Total plate carried on arc (j,k) by aircraft type a on route r
OBJ	Objective is to minimize total cost;
Binary Variables	X, Y, PC, VC
Integer Variable	Z
Free Variable	OBJ;

EQUATIONS

FLOWCONSERVATION_SOURCE(i,m)	Flow conservation for source nodes
FLOWCONSERVATION_DESTINATION(i,m)	Flow conservation for destination nodes
FLOWCONSERVATION_ENROUTE(i,m)	Flow conservation constraints for enroute nodes
WEIGHT_CAP(r,j,k,a)	Weight Capacity Constraints for arc (j,k) on route r for aircraft type a
TAKEOFF_WEIGHT_CAP(r,j,k,a)	Maximum Takeoff Weight for arc (j,k) on route r
VOLUME_CAP_C130(r,j,k)	Volume capacity of arc (j,k) on route r for aircraft type c130
VOLUME_CAP_C160(r,j,k)	Volume capacity of arc (j,k) on route r for aircraft type c160
VOLUME_CAP_CN235(r,j,k)	Volume capacity of arc (j,k) on route r for aircraft type cn235
VOLUME_CONFIG(r,j,k,a,b)	Volume configuration for all routes, route arcs and aircraft types and numbers
VOLUME_CONFIG_1(r,j,k,a)	Volume configuration 1 for all routes, route arcs and aircraft types
VOLUME_CONFIG_2(r,j,k,a,c)	Volume configuration 2 for all routes, route arcs and aircraft types
VOLUME_CONFIG_3(r,j,k,a,c)	Volume configuration 3 for all routes, route arcs and aircraft types
VOLUME_CONFIG_4(r,j,k,a,c)	Volume configuration 4 for all routes, route arcs and aircraft types
VOLUME_CONFIG_5(r,j,k,a,c)	Volume configuration 5 for all routes, route arcs and aircraft types
PAX_CAP_C130(r,j,k)	Passenger capacity of the arc (j,k) on route r for aircraft type c130
PAX_CAP_C160(r,j,k)	Passenger capacity of the arc (j,k) on route r for aircraft type c160

PAX_CAP_CN235(r,j,k)	Passenger capacity of the arc (j,k) on route r for aircraft type cn235
PAXCONFIG(r,j,k,a,b)	Pax configuration constraint for all routes, route arcs and aircraft types and numbers
PAXCONFIG_1(r,j,k,a)	Pax configuration 1 for all routes, route arcs and aircraft types
PAXCONFIG_2(r,j,k,a,c)	Pax configuration 2 for all routes, route arcs and aircraft types
PAXCONFIG_3(r,j,k,a,c)	Pax configuration 3 for all routes, route arcs and aircraft types
PAXCONFIG_4(r,j,k,a,c)	Pax configuration 4 for all routes, route arcs and aircraft types
PAXCONFIG_5(r,j,k,a,c)	Pax configuration 5 for all routes, route arcs and aircraft types
PLATE_CAP_C130(r,j,k)	Plate capacity of the arc (j,k) on route r for aircraft type c130
PLATE_CAP_C160(r,j,k)	Plate capacity of the arc (j,k) on route r for aircraft type c160
PLATE_CAP_CN235(r,j,k)	Plate capacity of the arc (j,k) on route r for aircraft type cn235
ROUTECONSERVATION(i,r,m)	Route Conservation Constraints
AIRCRAFTASSGN(r)	Aircraft assignment constraint for all routes
AIRCRAFTSUPPLY(a,r)	Available aircraft a for route r
SERVICELEVEL(pr)	Service level for priority pr
SERVICE_LEVEL_PERCENT(pr)	Service level percent of priority pr
TOTAL_WEIGHT_ON_ARC(r,j,k)	Total weight carried on arc (j,k)
TOTAL_WEIGHT_ON_ARC_ON_AIRCRAFT(a,r,j,k)	Total weight carried on arc (j,k) by aircraft type a on route r
TOTAL_PAX_ON_ARC(a,r,j,k)	Total pax carried on arc (j,k) by aircraft type a on route r
TOTAL_PLATE_ON_ARC_C130(r,j,k)	Total plate carried on arc (j,k) by aircraft type C130 on route r
TOTAL_PLATE_ON_ARC_C160(r,j,k)	Total plate carried on arc (j,k) by aircraft type C160 on route r

TOTAL_PLATE_ON_ARC_CN235(r,j,k)	Total plate carried on arc (j,k) by aircraft type CN235 on route r
OBJECTIVE_FUNCTION	Objective function;

***Flow conservation constraint set for source nodes**

```
FLOWCONSERVATION_SOURCE (i,m)$s(i,m)..
Sum((a,j,k)$F(i,j,k),y(m,a,j,k))-Sum((a,j,k)$P(i,j,k),y(m,a,j,k)) =e= x(m);
```

***Flow conservation constraint set for destination nodes**

```
FLOWCONSERVATION_DESTINATION (i,m)$d(i,m)..
Sum((a,j,k)$F(i,j,k),y(m,a,j,k))-Sum((a,j,k)$P(i,j,k),y(m,a,j,k)) =e= -x(m);
```

***Flow conservation constraint set for enroute nodes**

```
FLOWCONSERVATION_ENROUTE(i,m)$(not s(i,m) and not d(i,m))..
Sum((a,j,k)$F(i,j,k),y(m,a,j,k))-Sum((a,j,k)$P(i,j,k),y(m,a,j,k)) =e= 0;
```

***Weight capacity constraints for all route, aircraft and arc combinations**

```
WEIGHT_CAP(r,j,k,a)$Routearc(r,j,k)..
Sum(m,(reqdata(m,"Wload")+reqdata(m,"Pax")*PAXW)*y(m,a,j,k)) =l=
routedata(r,a,"WCAP")*z(r,a);
```

***Takeoff weight capacity constraints for all route, aircraft and arc combinations**

```
TAKEOFF_WEIGHT_CAP(r,j,k,a)$Routearc(r,j,k)..
Sum(m,(reqdata(m,"Wload")+reqdata(m,"Pax")*PAXW)*y(m,a,j,k)) =l= (routedata(r,a,"WTakeoff")-
fuelweight(a,j,k))*z(r,a);
```

***Volume capacity constraints for all route, aircraft and arc combinations**

```
VOLUME_CAP_C130(r,j,k)$Routearc(r,j,k)..
Sum(m,(reqdata(m,"Vload"))*y(m,"c130",j,k))  =l=
VOLEFF*(Sum(b,(15* VC(r,j,k,"c130","2",b)+30* VC(r,j,k,"c130","3",b) +
45* VC(r,j,k,"c130","4",b)+60*VC(r,j,k,"c130","5",b)+75* VC(r,j,k,"c130","6",b))) +
11*z(r,"c130"));
```

```
VOLUME_CAP_C160(r,j,k)$Routearc(r,j,k)..
Sum(m,(reqdata(m,"Vload"))*y(m,"c160",j,k)) =l=
VOLEFF*(Sum(b,(15* VC(r,j,k,"c160","2",b)+30* VC(r,j,k,"c160","3",b) +
```

```
45* VC(r,j,k,"c160","4",b)+60*VC(r,j,k,"c160","5",b)+75* VC(r,j,k,"c160","6",b))) +
11*z(r,"c160"));


VOLUME_CAP_CN235(r,j,k)$Routearc(r,j,k)..
Sum(m,(reqdata(m,"Vload"))*y(m,"cn235",j,k)) =l=
VOLEFF*Sum(b,(10* VC(r,j,k,"cn235","2",b)+ 20*VC(r,j,k,"cn235","3",b) +
30*VC(r,j,k,"cn235","4",b)))+ 6*z(r,"cn235");


*Volume configuration constraint for all route arc and aircraft types

VOLUME_CONFIG(r,j,k,a,b)$Routearc(r,j,k)..Sum(c,VC(r,j,k,a,c,b)) =l= 1;

VOLUME_CONFIG_1(r,j,k,a)$Routearc(r,j,k)..Sum((b,c),VC(r,j,k,a,c,b)) =e= z(r,a);

VOLUME_CONFIG_2(r,j,k,a,c)$Routearc(r,j,k).. VC(r,j,k,a,c,"1") =g= VC(r,j,k,a,c,"2");

VOLUME_CONFIG_3(r,j,k,a,c)$Routearc(r,j,k).. VC(r,j,k,a,c,"2") =g= VC(r,j,k,a,c,"3");

VOLUME_CONFIG_4(r,j,k,a,c)$Routearc(r,j,k).. VC(r,j,k,a,c,"3") =g= VC(r,j,k,a,c,"4");

VOLUME_CONFIG_5(r,j,k,a,c)$Routearc(r,j,k).. VC(r,j,k,a,c,"4") =g= VC(r,j,k,a,c,"5");


*Passenger capacity constraints for all route, aircraft and arc combinations

PAX_CAP_C130(r,j,k)$Routearc(r,j,k)..
Sum(m,(reqdata(m,"Pax"))*y(m,"c130",j,k))  =l=
Sum(b,(16* PC(r,j,k,"c130","2",b)+32* PC(r,j,k,"c130","3",b) +
50* PC(r,j,k,"c130","4",b)+ 68* PC(r,j,k,"c130","5",b)+90* PC(r,j,k,"c130","6",b)));


PAX_CAP_C160(r,j,k)$Routearc(r,j,k)..
Sum(m,(reqdata(m,"Pax"))*y(m,"c160",j,k))  =l=
Sum(b,(18* PC(r,j,k,"c160","2",b)+36* PC(r,j,k,"c160","3",b)+63* PC(r,j,k,"c160","4",b)+
81* PC(r,j,k,"c160","5",b)+ 91* PC(r,j,k,"c160","6",b)));


PAX_CAP_CN235(r,j,k)$Routearc(r,j,k)..
Sum(m,(reqdata(m,"Pax"))*y(m,"cn235",j,k)) =l=
Sum(b,(16* PC(r,j,k,"cn235","2",b)+32* PC(r,j,k,"cn235","3",b)+ 48*PC(r,j,k,"cn235","4",b)));


*Pax configuration constraint for all route arc and aircraft types

PAXCONFIG(r,j,k,a,b)$Routearc(r,j,k)..Sum(c,PC(r,j,k,a,c,b)) =l= 1;

PAXCONFIG_1(r,j,k,a)$Routearc(r,j,k).. Sum(b,Sum(c,PC(r,j,k,a,c,b))) =e= z(r,a);
```

```
PAXCONFIG_2(r,j,k,a,c)$Routearc(r,j,k).. PC(r,j,k,a,c,"1") =g= PC(r,j,k,a,c,"2");

PAXCONFIG_3(r,j,k,a,c)$Routearc(r,j,k).. PC(r,j,k,a,c,"2") =g= PC(r,j,k,a,c,"3");

PAXCONFIG_4(r,j,k,a,c)$Routearc(r,j,k).. PC(r,j,k,a,c,"3")=g= PC(r,j,k,a,c,"4");

PAXCONFIG_5(r,j,k,a,c)$Routearc(r,j,k).. PC(r,j,k,a,c,"4") =g= PC(r,j,k,a,c,"5");

*Plate capacity of the arc (j,k) on route r for aircraft type c130

PLATE_CAP_C130(r,j,k)$Routearc(r,j,k)..
Sum(b,PC(r,j,k,"c130","2",b)+2*PC(r,j,k,"c130","3",b)+3* PC(r,j,k,"c130","4",b) +
4* PC(r,j,k,"c130","5",b)+5* PC(r,j,k,"c130","6",b)+ VC(r,j,k,"c130","2",b) +
2*VC(r,j,k,"c130","3",b)+3* VC(r,j,k,"c130","4",b)+ 4* VC(r,j,k,"c130","5",b) +
5* VC(r,j,k,"c130","6",b)) =l= PlateCAP("c130")*z(r,"c130");



*Plate capacity of the arc (j,k) on route r for aircraft type c160

PLATE_CAP_C160(r,j,k)$Routearc(r,j,k)..
Sum(b,PC(r,j,k,"c160","2",b)+2*PC(r,j,k,"c160","3",b)+3* PC(r,j,k,"c160","4",b) +
4* PC(r,j,k,"c160","5",b)+5* PC(r,j,k,"c160","6",b)+ VC(r,j,k,"c160","2",b) +
2*VC(r,j,k,"c160","3",b)+3* VC(r,j,k,"c160","4",b)+ 4* VC(r,j,k,"c160","5",b) +
5* VC(r,j,k,"c160","6",b)) =l= PlateCAP("c160")*z(r,"c160");



*Plate capacity of the arc (j,k) on route r for aircraft type cn235

PLATE_CAP_CN235(r,j,k)$Routearc(r,j,k)..
Sum(b,PC(r,j,k,"cn235","2",b)+2*PC(r,j,k,"cn235","3",b)+3* PC(r,j,k,"cn235","4",b) +
VC(r,j,k,"cn235","2",b)+2*VC(r,j,k,"cn235","3",b)+3*VC(r,j,k,"cn235","4",b)) =l=
PlateCAP("cn235")*z(r,"cn235");



*Route conservation constraints for all movement requirements for node i on route r

ROUTECONSERVATION (i,r,m)..
Sum((a,j,k)$((P(i,j,k)$Rarcs(j,k)) and Rarcs(j,k)$Routearc(r,j,k)),y(m,a,j,k)) +
Sum((a,j,k)$((F(i,j,k)$Rarcs(j,k)) and not Rarcs(j,k)$Routearc(r,j,k)),y(m,a,j,k)) =l= x(m);



*Aircraft assignment constraint for all routes

AIRCRAFTASSGN(r).. Sum (a,z(r,a)) =G= 0 ;



*Available number of aircraft a for route r

AIRCRAFTSUPPLY(a,r).. z(r,a) =l= SUPPLY(a,r);
```

***Service level constraint set for movement requirements for corresponding priority level**

```
SERVICELEVEL(pr).. Sum (m$prio (m, pr), x (m)) =g=SERLEVEL (pr)*Numpr (pr);
```

***Service level percent of priority pr**

```
SERVICE_LEVEL_PERCENT(pr)..  SL(pr)*NUMPR(pr) =g= Sum(m$prio(m,pr),x(m));
```

*** Total weight carried on arc (j,k) by aircraft type a on route r**

```
TOTAL_WEIGHT_ON_ARC_ON_AIRCRAFT(a,r,j,k)$RouteAircraft(a,r,j,k)..
WTA(a,j,k) =g= Sum(m,(reqdata(m,"Wload")+reqdata(m,"Pax")*PAXW)*y(m,a,j,k));
```

```
TOTAL_WEIGHT_ON_ARC(r,j,k)$Routearc(r,j,k)..
WT(j,k) =g= Sum((m,a),(reqdata(m,"Wload")+reqdata(m,"Pax")*PAXW)*y(m,a,j,k));
```

***Total pax carried on arc (j,k) by aircraft type a on route r**

```
TOTAL_PAX_ON_ARC(a,r,j,k)$RouteAircraft(a,r,j,k)..
PT(a,j,k) =g= Sum(m,reqdata(m,"Pax")*y(m,a,j,k));
```

***Total plate carried on arc (j,k) by aircraft type a on route r**

```
TOTAL_PLATE_ON_ARC_C130(r,j,k)$Routearc(r,j,k)..
PLT("C130",j,k)  =e= Sum(b, PC(r,j,k,"c130","2",b)+2*PC(r,j,k,"c130","3",b) +
3* PC(r,j,k,"c130","4",b)+4* PC(r,j,k,"c130","5",b)+5* PC(r,j,k,"c130","6",b) +
VC(r,j,k,"c130","2",b)+2*VC(r,j,k,"c130","3",b)+3* VC(r,j,k,"c130","4",b) +
4* VC(r,j,k,"c130","5",b)+5* VC(r,j,k,"c130","6",b));
```

```
TOTAL_PLATE_ON_ARC_C160(r,j,k)$Routearc(r,j,k)..
PLT("C160",j,k)  =e= Sum(b, PC(r,j,k,"c160","2",b)+2*PC(r,j,k,"c160","3",b) +
3* PC(r,j,k,"c160","4",b)+4* PC(r,j,k,"c160","5",b)+5* PC(r,j,k,"c160","6",b) +
VC(r,j,k,"c160","2",b)+2*VC(r,j,k,"c160","3",b)+3* VC(r,j,k,"c160","4",b) +
4* VC(r,j,k,"c160","5",b)+5* VC(r,j,k,"c160","6",b)) ;
```

```
TOTAL_PLATE_ON_ARC_CN235(r,j,k)$Routearc(r,j,k)..
PLT("CN235",j,k) =e= Sum(b, PC(r,j,k,"cn235","2",b)+2*PC(r,j,k,"cn235","3",b) +
3* PC(r,j,k,"cn235","4",b)+ VC(r,j,k,"cn235","2",b)+ 2*VC(r,j,k,"cn235","3",b) +
3* VC(r,j,k,"cn235","4",b));
```

```
OBJECTIVE_FUNCTION..OBJ=E= Sum((r,a),(Rcost(r,a))*z(r,a));

OPTION LIMROW = 100;

MODEL CARGOASSIGNMENTPROBLEM /ALL/;

SOLVE CARGOASSIGNMENTPROBLEM USING MIP MINIMIZING OBJ;
```

APPENDIX C

AN EXAMPLE TEST INSTANCE

Table C.1 An Example Test Instance Used for Experiments

Req. No.	Ori.	Dest.	ALT	LDT	W (kg)	V (m^3)	P	Prio
1	13	8	96	116	164	0.3644	4	2
2	10	5	0	44	810	1.8000	0	2
3	9	10	24	116	60	0.1333	4	2
4	9	7	96	116	159	0.3533	2	2
5	8	9	72	90	2,821	6.2689	0	1
6	5	6	24	116	11	0.0244	1	3
7	10	8	24	90	230	0.5111	0	4
8	3	10	72	116	17	0.0378	0	5
9	1	8	96	116	46	0.1022	0	5
10	8	7	24	90	143	0.3178	4	2
11	13	7	24	116	0	0.0000	1	2
12	5	9	24	44	872	1.9378	4	2
13	10	3	72	116	200	0.4444	0	4
14	10	3	72	90	1,700	3.7778	0	1
15	3	13	72	116	1	0.0022	0	5
16	10	8	96	116	350	0.7778	0	3
17	10	8	24	90	300	0.6667	4	2
18	10	9	24	90	570	1.2667	2	2
19	10	12	0	44	550	1.2222	4	2
20	7	8	96	116	597	1.3267	0	2
21	2	8	0	116	57	0.1267	0	5
22	6	8	96	116	48	0.1067	5	2
23	13	12	96	116	190	0.4222	5	2
24	10	7	96	116	200	0.4444	7	1
25	2	3	72	116	73	0.1622	0	5
26	10	2	0	44	500	1.1111	0	2
27	5	3	72	116	1	0.0022	0	5
28	3	13	0	116	30	0.0667	0	5
29	9	5	72	90	244	0.5422	13	1
30	9	8	24	90	128	0.2844	2	2
31	2	6	72	116	62	0.1378	0	5
32	5	10	24	44	516	1.1467	1	2
33	11	12	96	116	1	0.0022	6	1
34	5	12	72	116	58	0.1289	0	5
35	10	1	72	116	250	0.5556	0	3
36	2	13	72	116	2	0.0044	0	5
37	8	10	72	116	183	0.4067	0	4
38	3	7	0	116	2	0.0044	0	5

Table C.1 (continued)

Req. No.	Ori.	Dest.	ALT	LDT	W (kg)	V (m^3)	P	Prio
39	12	5	0	116	137	0.3044	0	4
40	12	3	0	116	42	0.0933	0	5
41	5	10	72	116	153	0.3400	0	4
42	8	3	0	116	122	0.2711	1	3
43	3	9	72	116	12	0.0267	0	5
44	9	8	24	90	153	0.3400	1	2
45	8	5	0	116	73	0.1622	1	2
46	8	13	96	116	6	0.0133	1	3
47	8	3	72	116	29	0.0644	2	2
48	9	8	24	116	110	0.2444	0	4
49	12	13	96	116	112	0.2489	0	4
50	13	8	96	116	1,030	2.2889	1	1
51	3	10	72	116	58	0.1289	0	5
52	8	11	96	116	92	0.2044	0	5
53	8	3	72	116	40	0.0889	1	3
54	3	2	0	116	3	0.0067	0	5
55	6	9	96	116	95	0.2111	6	1
56	12	10	96	116	844	1.8756	15	1
57	2	7	72	116	1	0.0022	0	5
58	10	11	96	116	460	1.0222	4	2
59	2	6	72	116	11	0.0244	0	5
60	8	2	0	116	1	0.0022	2	2
61	2	3	72	116	193	0.4289	0	4
62	9	10	96	116	225	0.5000	1	3
63	13	8	24	90	274	0.6089	0	3
64	13	9	96	116	28	0.0622	4	2
65	10	12	0	116	70	0.1556	2	2
66	10	2	0	90	250	0.5556	0	3
67	1	8	0	116	150	0.3333	0	4
68	10	13	24	90	160	0.3556	3	2
69	9	13	24	116	60	0.1333	1	3
70	10	11	96	116	130	0.2889	2	2
71	10	1	0	116	100	0.2222	0	4
72	10	8	24	90	200	0.4444	0	4
73	12	9	0	44	840	1.8667	0	2
74	8	5	72	116	54	0.1200	0	5
75	9	6	96	116	231	0.5133	4	2
76	9	10	96	116	322	0.7156	0	3
77	9	6	24	90	339	0.7533	7	1
78	8	9	72	116	50	0.1111	0	5

Table C.1 (continued)

Req. No.	Ori.	Dest.	ALT	LDT	W (kg)	V (m^3)	P	Prio
79	9	13	96	116	144	0.3200	0	4
80	10	9	96	116	870	1.9333	2	2
81	8	9	96	116	214	0.4756	0	4
82	9	2	0	116	85	0.1889	0	5
83	6	9	96	116	52	0.1156	15	1
84	8	1	72	116	86	0.1911	2	2
85	5	2	72	116	3	0.0067	0	5
86	10	12	96	116	650	1.4444	0	2
87	9	5	72	90	743	1.6511	3	2
88	10	7	96	116	100	0.2222	4	2
89	8	10	96	116	21	0.0467	6	1
90	6	10	96	116	104	0.2311	26	1
91	7	9	24	90	401	0.8911	2	2
92	8	9	24	116	161	0.3578	0	4
93	8	12	96	116	13	0.0289	1	2
94	1	7	96	116	1	0.0022	0	5
95	10	7	96	116	490	1.0889	4	2
96	2	9	72	116	69	0.1533	0	5
97	9	3	0	44	595	1.3222	0	2
98	12	6	96	116	22	0.0489	0	5
99	10	3	0	116	70	0.1556	0	5
100	12	13	96	116	489	1.0867	0	3
101	3	7	72	116	1	0.0022	0	5
102	7	10	96	116	624	1.3867	13	1
103	10	2	72	116	80	0.1778	0	5
104	7	9	24	90	219	0.4867	0	4
105	8	6	96	116	40	0.0889	6	1
106	6	9	96	116	104	0.2311	6	1
107	8	2	0	116	89	0.1978	0	5
108	9	6	96	116	438	0.9733	4	2
109	10	1	72	116	110	0.2444	0	4
110	2	8	72	116	88	0.1956	0	5
111	10	1	72	90	500	1.1111	0	2
112	8	6	24	90	330	0.7333	2	2
113	6	10	24	44	4,130	9.1778	21	1
114	8	7	24	90	145	0.3222	0	4
115	6	7	96	116	0	0.0000	13	1
116	8	9	24	116	39	0.0867	0	5
117	10	6	96	116	1,300	2.8889	14	1
118	8	12	96	116	11	0.0244	1	3

Table C.1 (continued)

Req. No.	Ori.	Dest.	ALT	LDT	W (kg)	V (m^3)	P	Prio
119	8	2	72	116	3	0.0067	0	5
120	5	7	72	90	400	0.8889	0	3
121	2	10	0	116	172	0.3822	0	4
122	8	2	72	116	82	0.1822	0	5
123	8	6	96	116	65	0.1444	0	5
124	9	3	72	116	8	0.0178	0	5
125	5	9	72	90	202	0.4489	0	4
126	1	9	96	116	7	0.0156	1	2
127	5	9	72	90	1,201	2.6689	0	1
128	8	4	24	116	1	0.0022	0	5
129	10	5	72	90	595	1.3222	3	2
130	8	9	96	116	16	0.0356	0	5
131	1	8	96	116	88	0.1956	1	2
132	9	3	0	116	42	0.0933	0	5
133	10	5	72	90	830	1.8444	5	2
134	8	10	96	116	35	0.0778	2	2
135	9	2	72	90	416	0.9244	0	3
136	13	6	24	116	55	0.1222	4	2
137	2	9	72	116	197	0.4378	0	4
138	8	12	0	116	1	0.0022	0	5
139	10	9	72	90	450	1.0000	0	3
140	2	1	72	116	0	0.0000	1	3
141	10	7	24	116	80	0.1778	4	2
142	13	11	96	116	50	0.1111	4	2
143	3	8	0	116	6	0.0133	0	5
144	3	12	72	116	1	0.0022	0	5
145	2	10	0	116	162	0.3600	0	4
146	7	8	24	116	3	0.0067	1	3
147	6	7	96	116	0	0.0000	14	1
148	3	12	72	116	33	0.0733	0	5
149	5	9	72	90	791	1.7578	0	2
150	10	3	72	90	1,760	3.9111	0	3