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A COMPUTERIZED ANALYTICAL DECISION SUPPORT SYSTEM FOR EVALUATING AIRLINE SCHEDULING INTERACTIONS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By
Chul Kyu Lee, B.S., M.B.A.A.

The Ohio State University
1999

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ABSTRACT

In the last decade, airlines have focused on increasing resource utilization to improve financial performance. To achieve such improvements, many airlines have employed the concept of revenue management technology. While revenue management technology is continuing to evolve, its basics are now widely practiced, and the associated benefits have been largely realized. As a result, airlines are now focusing attention on another area – schedule optimization. They are finding that improving their schedule development processes improves the quality and profitability of their schedules. This shift in focus has spurred a great deal of interest in automated tools and decision-support systems that enhance the schedule development process. Airline scheduling can be defined as the art of synthesizing a multiplicity of interrelated factors in order to achieve a balanced pattern of flight segments that will yield the maximum of some value, such as market share or segment/network profit.

The dissertation involves the development of a computerized airline schedule analysis and planning system intended to assist current and future airline managers.
The primary objective of the dissertation is to develop comprehensive algorithms that can provide a framework for developing a PC-based computerized decision support system for learning about the airline scheduling process. This framework takes into consideration factors that affect capacity and demand as well as factors that affect aircraft and airport operations. This system is designed to be used as a learning tool for students and entry-level practitioners such that it allows its users to learn the intricacies of the airline scheduling practice — not only the basics, such as operational feasibility, but also the sensitivity and interaction of a wide set of key variables.

The research has been divided into three phases. The first phase involves identifying critical factors that affect the scheduling process. The second phase develops algorithms that can be used to generate a complete set of airline schedules and match capacity to demand in markets based on several predetermined passenger choice parameters, such as frequency of flight service, time of day preferences, aircraft type preferences, types of flight itinerary (nonstop direct/multi-stop direct/intraline connection/interline connection), and number of en route stops. This algorithm also allows for (1) a sensitivity analysis of airline operating costs and revenues to changes in schedules, and (2) the development of an aircraft fleet assignment plan and an aircraft routing plan. The last phase of the research involves the development of a computerized decision support system, using the above algorithms to provide a systematic interaction among its users and standardized databases of information pertinent to all relevant functions of the airline, as well as a standardized interactive graphical user interface (GUI) for schedule generation.
The entire schedule planning system is composed of three main sub-systems, each of which comprised of several sub-modules. The first system is the airline schedule development system which generates a complete airline schedule with a set of given flight information. As an initial planning process, only an aircraft type is assigned to each flight segment without specifying a specific aircraft (called tail numbers in the industry). This system then determines a feasible number of aircraft by each aircraft type and generates a complete weekly aircraft routing plan of each aircraft. It also creates single and double connections from a direct flight schedule. Once a complete airline schedule is developed, the market share and passenger allocation system determines the market share of each airline for every city pair, allocates passengers to each flight, and identifies the types of passengers on any nonstop flight segment of the following types: local, through, and connecting traffic. Passenger revenues and operating costs are also determined in this system. Finally, the report generator system will generate the following reports: segment/network profitability report, operating statistics report, and income statement.

This decision support system will help academicians train airline managers how to plan and prepare for today's highly competitive and rapidly changing environment. The airline scheduling module, developed by the author, has been used in an undergraduate class as a tool that provides students with hands-on experience in developing airline schedules and determining their effect on airline's operating performance.
DEDICATION

To my family
ACKNOWLEDGMENTS

I would first like to thank my adviser, Dr. Nawal Taneja, for being a constant source of inspiration, a role model, and a mentor. I am deeply grateful for his valuable advice and insights, which went beyond the call of his adviser duties.

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My family deserves my final and deepest expression of gratitude. I want to thank my father and mother for their continuing support throughout my entire education. My beloved wife, Miryung, has provided a constant source of encouragement and inspiration. I also want to thank the rest of my family members including my parents-in-law, my brother, and my sister for their support. Finally, I want to thank my two adorable children, Stephen and Lois for providing my family a joy of life.
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CHAPTER 1

INTRODUCTION

1.1 Research Objectives and Motivation

The airline schedule planning problem is defined as the sequence of decisions that need to be made to make a flight schedule operational. In order to match fixed capacity with variable demand, airlines need analytical planning systems to minimize risks and maximize opportunities on a network basis taking into consideration all operational constraints. Given the high level of competition in the airline industry, effective decision making is crucial to the profitability of an airline. As a result, most airlines have started focusing on schedule optimization on a more timely-basis. This has been one of the motivations of this dissertation in which we concentrate on airline schedule planning problems and attempt to integrate the decision making process. The primary objective of this dissertation is to establish comprehensive algorithms that can be used as methods that can provide a framework in developing a PC-based computerized decision support system for the airline scheduling development process. Another aim of the dissertation is to achieve a simultaneous rather than sequential solution, because a simultaneous solution will generate more economical solutions and form less incompatibilities among the decisions. The computerized system can be used not only as a tool to develop
and evaluate airline schedule to determine how a change in each scheduling variable can affect the overall airline operation, but it is also a tool to teach students, and current airline practitioners the concept and actual tactics of airline scheduling process as well as sensitivities to key variables.

Deregulation of U.S. airline industry in 1978 has not only made the industry extremely competitive, but also opened up many opportunities to many airlines. Prior to deregulation, competition among carriers was limited by the Civil Aeronautics Board (CAB) in two of the three major areas of airline marketing — route authority and pricing — leaving only the frequency of flight schedule made available by any one carrier over any one route up to individual airline’s management decision. Competition, therefore, was limited to frills, such as fancy meals and luxurious first class lounge, and unnecessary high frequency of flight (i.e. too many flights in thin markets). Competition in these areas made airline operations inefficient by increasing airline’s operating costs. However, with the advent of deregulation, airlines suddenly found themselves facing new forms of competition. New, low-cost, nonunion carriers sprung up in major markets offering air transportation at unrestricted fares from 30 to 75% below existing fares. In addition to more competition, airlines also received many freedoms to optimize their networks. These airlines were now allowed to have the right to choose not only schedules, and aircraft size (type), but also the network of routes and fares. New freedom and ever-increasing competition has greatly increased the number of design variables available to each airline. Each of these activities is a sub-problem of the total airline schedule design problem.
Since the 1950's, operations researchers have come up with many independent methods for dealing with airline scheduling problems [97]. Some of these have been published in the relatively inaccessible Proceedings of AGIFORS (Airline Group, International Federation of Operational Research Societies), documented in internal company reports, or not published at all. One characteristic of these scheduling tools is that each algorithm is developed with its own input, output, and database structure, user interface, and computer hardware and software requirements. This characteristic means that some of those scheduling tools are being under-utilized because they are cumbersome and not integrated with each other. Furthermore, consideration of aircraft routings, hub "banking", crews, maintenance planning, gate allocation, slot restrictions, and the marketing needs of the customer, complicate scheduling to the point that the problems are not solvable by one closed-form optimization technique. Changing an established schedule, let alone creating one, may involve a tremendous amount of work. Typically, an airline's complex schedule is not produced from scratch but is the culmination of years of manual routine addition and enhancement starting from a relatively simple model. The manual system of schedule updating is a tedious process relying on a team of experienced schedulers toiling continuously and trying to conform to the various constraints. Therefore, developing a system that can be used as a tool not only to construct and evaluate a complete airline schedule, but also to teach a concept and an actual airline scheduling process to students or others who are either involved with or interested in the area of airline management has been not only a main objective, but also major motivation to initiate this dissertation.
The solution to the scheduling problem should be a systematic interaction between the human, standardized databases for information which affects all functions of the airline, powerful desktop workstations for decision support, a standardized interactive graphical user interface for schedule generating and editing, and the operations research technique for optimization. The airline schedule development system (Figure 1.1) developed as the core of this dissertation is designed to provide a seamless method of communications across all scheduling related functions: route system planning, flight schedule generation, fleet assignment (aircraft assignment), connection generation, market share forecasting, passenger allocation, and revenue/cost generation. This integration is made possible through a common interface and database structure among each of these modules.

![Diagram of Airline Schedule Development System](image)

*Figure 1.1: Airline Schedule Development System*
1.2 Scope of the Research

This section discusses the scope of the dissertation and also the global limitations and assumptions of the airline schedule development system. The airline schedule development system was initially developed to integrate many design and decision variables that are required to develop an airline schedule and evaluate its performance in terms of segment and network-based profitability. There can be literally unlimited number of decision variables that can be considered in developing airline schedules. Therefore, several global assumptions had to be made to determine which design and decision variables should be included in the schedule development mainly because of the complexity of some of the decision variables and the lack of data availability.

Figure 1.2 illustrates some of more important decision variables among these factors that go into an airline scheduling process. Some of these variables can be easily quantified. Others are very difficult to quantify and integrate into a proposed schedule development system. Some of quantifiable factors are aircraft-related variables such as cabin configuration, performance characteristics, and equipment maintenance requirements, airport-related variables such as runway length/altitude, slot constraint, curfews, and landing fees, geographical variables such as time zone changes, longitude/latitude, and some of marketing factors such as flight frequency and time-of-day travel demand variations. Then, we have some factors that are difficult to be quantified. Some of these factors are frequent flier program, some air cargo constraints (U.S. Postal Service contract), travelers’ preferences to certain carriers and airports, and constraints set by others such as local communities and travel agents. It is impossible to integrate all the decision variables into a proposed schedule development system because
Strategic Decision

1. Forecast of national/world economy
2. Traffic forecast in each market
3. Growth plan for an airline
4. Future fleet planning
5. Plan for strategic alliance and code-sharing with other carriers

Market-related variables
1. Traffic demand forecast by true O-D:
   - type of traffic: passenger(pax.)/cargo
   - type of pax. market: business/leisure
2. Traffic rights to certain countries
3. Seasonality factors
4. Time of day demand variation

Competition-related variables
1. OAG schedules:
   - type of flights: nonstop/multi-stop/connection
   - frequency: flight itinerary; equipment
2. Type of competing airlines: major or low-cost carriers
3. Competition by services: fare discount & amenity

Airport-related variables
1. Geographical position:
   - longitude/latitude & altitude
   - time zone changes & day-light saving time
2. Runway restrictions: length
3. Slot constraints & connecting complexes at hub airports
4. Ground handling equipment & catering service
5. ATC restrictions: delays & congestion at certain airports
6. Ticket counter/gate availability

Aircraft-related variables
1. Aircraft performance
   - range, speed, seat capacity, & fuel capacity
   - airport compatibility
2. Aircraft version:
   - all passenger/cargo/combi
3. Cabin configuration:
   - first/business/coach classes
4. Cockpit/cabin crew availability

Other variables
1. Local communities:
   - type of city: business district/ vacation spot/ mixed
   - restriction: noise
2. Requests by certain organizations
   - hotel & motel operators
   - travel agents

Generate Airline Schedule

(*) Italics: variables implemented in the system

Figure 1.2: Conceptual framework for airline schedule development process
of the complexity of some of the decision variables and the lack of data availability to a researcher.

As an initial stage of the research process, several global assumptions had to be made to determine which design and decision variables should be included in the schedule development. First, a decision had to be made to determine the type of traffic that would be considered within the system. As shown in Figure 1.2, there are two major types of traffic in air transportation: passenger and cargo. Even though most major U.S. air carriers’ main source of revenues, with the exception of air cargo freight companies such as Federal Express, come from carrying passengers domestically or internationally, there are several foreign carriers, such as Korean Air, KLM, Air France, and Lufthansa, that generate a larger portion of their revenues by carrying cargo on either all cargo planes or passenger-cargo combi-airplanes. Table 1.1 illustrates the significant differences in the cargo revenue contributions to total revenues among several major airlines in 1997 and 1998.

<table>
<thead>
<tr>
<th>Revenue Type</th>
<th>United Airlines&lt;sup&gt;1&lt;/sup&gt;</th>
<th>American Airlines&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Southwest Airlines&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Korean Air&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Dutch KLM&lt;sup&gt;3&lt;/sup&gt;</th>
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<tr>
<td>Passenger</td>
<td>$15,213.7</td>
<td>$14,690.5</td>
<td>$3,963.8</td>
<td>$1,850</td>
<td>$4,906</td>
</tr>
<tr>
<td>Cargo</td>
<td>$513.2</td>
<td>$400.5</td>
<td>$45.6</td>
<td>$774</td>
<td>$989</td>
</tr>
<tr>
<td>Other&lt;sup&gt;4&lt;/sup&gt;</td>
<td>$1,303</td>
<td>$921.4</td>
<td>$143.3</td>
<td>$405</td>
<td>$787</td>
</tr>
<tr>
<td>Total</td>
<td>$17,029.9</td>
<td>$16,012.4</td>
<td>$4,152.6</td>
<td>$3,029</td>
<td>$6,682</td>
</tr>
<tr>
<td>% of Cargo Revenues</td>
<td>3%</td>
<td>2.5%</td>
<td>1.1%</td>
<td>25.6%</td>
<td>14.8%</td>
</tr>
</tbody>
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(All figures are millions in U.S. dollars)

*Table 1.1: Percentage of cargo revenues*

---


<sup>4</sup> Other revenues include revenues generated by maintenance work, cargo and mail handling, duty-free sales, and aircraft handling.
However, considering both passenger and cargo revenues in the system would make the system too complex and cumbersome because the algorithms that can be applied to demand forecast, market share analysis, traffic allocation, and profit analysis of cargo traffic are totally different from passenger traffic. Therefore, it was determined at the beginning stage of the research that only passenger traffic would be in the system. However, as a future study, it would make the system much more realistic if cargo traffic could be incorporated into the system since the contribution of cargo could make a marginal flight truly profitable.

Passenger traffic can further be divided into sub-groups. On any given flight, an aircraft usually is configured in several classes, depending on the type of a flight and an airline, even though there are some airlines that only offer a single cabin class of service (coach or economy class), Southwest Airlines being the most famous of this type of airlines. The most common aircraft configuration for domestic flights of scheduled airlines is a combination of coach class and a small section of first class. For an international flight, there are usually three classes: economy, business, and first. However, there are some airlines, such as EVA Air, that have four classes. However, passenger traffic demand for each of these classes are rarely available and an algorithm to allocate passengers to each cabin class seems to be cumbersome. Therefore, it is assumed all aircraft are configured in only a single class, namely coach class. This assumption was made simply because it would require many more iterations of the same procedure if different cabin classes are considered, which could entail a great deal of computing time. Implementing a new algorithm should be the same whether a single cabin or multi cabin
classes are considered. Another assumption is that the system only deals with scheduled commercial airlines and it excludes charter carriers and fixed based operators (FBO).

There are three major assignment problems in the area of airline scheduling: fleet assignment, aircraft maintenance routing, and crew scheduling. In an aircraft routing problem, the problem of routing aircraft so that safety standards are satisfied is defined as an aircraft maintenance routing problem. Crew scheduling refers to the creation of schedule plans for both cockpit and cabin crew members by assigning them to particular flights based on several predetermined constraints. Incorporating the aircraft maintenance routing and crew scheduling problems into a system is not an impossible task. However, it will take great efforts to augment an algorithm to add the maintenance routing problem to the existing system. Both aircraft maintenance routing and crew scheduling itself have been subjects of several dissertations. Therefore, it is assumed that the basic fleet assignment is sufficient to cover the basic aircraft maintenance schedule and the system does not consider the crew scheduling problem in developing an airline flight schedule.

As discussed in the previous section, excluding cargo traffic, aircraft maintenance routing problem, and crew scheduling problem in executing the system is the major global assumption that had to be made to keep the research manageable. In addition to these global assumptions, there are several operational restrictions and limits in the scheduling system that should be addressed.

This scheduling system is designed neither to forecast actual traffic (passenger or cargo) demand nor to set actual fares between two cities. However, the system forecasts the market share of each airline and attractiveness each flight for all the true origin-
destination markets. Based on each flight’s attractiveness, the system also determines (forecasts) passenger allocation on each nonstop flight segment by each true origin-destination (O&D) pair. In other words, this research does not attempt to develop a model to forecast primary (aggregate) demands. Rather, this system forecasts secondary demands that are related to passenger preference. Even though the system is not designed to determine the actual fare level in each market, a basic fare computing algorithm is embedded in the system to perform an airline network profit analysis.

The most significant and important product an airline is selling to the traveling public is a seat on a commercial aircraft. Then, a certain number of seats, depending on aircraft size and each airline’s preferred cabin configuration, constitute a particular flight from one point to another. Just like any other industry, airlines try to make their product, flight service between two points people want to travel, more attractive than their competitors’ products to capture a larger market share. Therefore, for an airline to make its product more appealing, an airline should improve the features that are associated with both external and internal images of an airline and each flight. There are many factors that could be considered in determining the attractiveness of each flight and the market share of each airline in every market.

In this dissertation, some of the factors that make up the characteristic of an individual airline or flight have been carefully analyzed to convert them into a form that can be incorporated into an algorithm which determines the attractiveness of an individual flight and ultimately the market share of each airline. However, not all the variables that were analyzed could be quantified. Therefore, some factors like those that are related to airline images and customer loyalty, such as a frequent flyer program, had
to be left out of the equation. Even though an airline’s frequent flyer program has played an important role in stimulating air travel demand, it is profoundly difficult and cumbersome to differentiate one airline from another to determine to which airlines are more attracted to travelers based on each airline’s frequent flyer program because almost every single airline, even a small carrier, offers some type of a frequent flyer program in one way or another. Obviously, the bigger an airline, the more wide variety of rewards it can provide, but it is still cumbersome and insignificant to rank the airlines by their frequent flyer programs.

The other factor which is also extremely hard to quantify is passenger’s perception to each airline’s image in terms of its safety records, brand recognition, marketing strategy, and advertising tactics. Therefore, even though the perception of an airline’s image is as important as any other factor, this factor has also been left out of the equation.

Since deregulation of the airline industry in 1978, U.S. airlines were given freedom to set their own fares in any market they flew and the fares had been a great way to differentiate one airline from another. However, with the advent of advanced computer technology in the areas of reservation systems and revenue management systems and extensive synchronized network systems among different reservation systems, airlines can and do match fares of their competitors instantaneously. Even though this tactic has raised some concerns among several consumer groups and the government, airlines could have been matching fares of competitors without creating serious accusations of wrongdoings. Therefore, it is safe to say that it is practically impossible to differentiate one airline from another based on the fare level. Another
reason why it is hard to quantify the fare into the form that can be incorporated into the algorithm that determines the attractiveness of a flight and the market share of an airline is due to the complex pricing structure of the airline industry. In the United States in 1986, an average of 68,000 fare changes per day were recorded. The average number of daily fare changes has increased by 400% to 340,000 in 1996. For these reasons, fare levels were not considered to be a factor that determine the attractiveness and the market share of an airline. However, it is not to say that the fare is not an important and significant determinant of air travel demand. It is probably the most significant variable that determines the future air travel demand along with the state of the economy.

The last global assumption that needs to be addressed is in the area of database structure. The developed airline scheduling system includes several databases. Even though an effort has been made to design the databases as comprehensive and up-to-date as possible, there were some limits on that. Therefore, the databases only contain the data that are available to the public. While some of the data are available free of charge, some of the data had to be purchased. However, each database can be easily modified and updated without any major change to the system to ensure that the system is not limited to the current databases.

Even though it was this decision support system is help academicians train airline managers how to plan and prepare for today's highly competitive and rapidly changing environment. As mentioned earlier, the airline scheduling module, developed by the author, has been used in an undergraduate class as a tool that provides students with hands-on experience in developing airline schedules and determining their effect on

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5 Source: Airline Tariff Publishing Company (ATPCO)
airline's operating performance. However, the author has not attempted to conduct a study that could evaluate the effectiveness of the developed system as a teaching tool. This study could be conducted in a classroom by assigning one half of a class to use the computer system to develop an airline schedule and the second half of the class to create the schedule manually. Then, each group's performance could be evaluated based on some criteria, such as time to develop the schedule, to measure the effectiveness of the developed computer system.

1.3 Introduction to the Airline Planning Process and Airline Productivity Measures

1.3.1 Airline Planning

Where an airline flies, how often it flies, and which aircraft it operates have never been more critical to profitability than it is today. The airline has to out-smart the competition by offering schedules passengers want, while utilizing the right mix of equipment and personnel. Because a reservation of a seat on an aircraft is an airline's primary product and a schedule is a way of delineating seats (flights in a broader term) to market them to the flying public, schedule development should be viewed as a well-defined, cyclical process that involves numerous interrelated, sequential steps, starting as early as two years before the schedule is published to the marketplace. Therefore, how often the schedule development process is executed is a major decision with strategic and competitive implications. Figure 1.3 shows the flow chart that illustrates the overall airline schedule planning process indicating how a strategic decision planning can be
coupled with a tactical decision process and the transition process from a long-term strategic decision planning to a short-term tactical planning stage.  

A strategy is a firm's unique set of decision rules for the development of its product/market/technology portfolio. Strategic planning is the process for setting guidelines for the purposeful pursuit of strategy. It must therefore include specification of:

- areas in which the firm aspires to do business
- competitive advantage of each area
- distinctive capabilities in each area
- synergy among and within areas
- method of growth

Having implied that strategic planning is the basis of the decision making process, airlines must establish what constitutes a strategic decision and how the decision making process works. Basically there are three classes of management decisions: strategic decision, administrative decision, and tactical decision related to day-to-day operations. Strategic decisions relate the firm to its environment so as to optimize the potential of its objectives. Administrative decisions are concerned with structuring a company for maximization of the potential of its objectives. Finally, operating decisions are concerned with the short term attainment of the tactical objectives of the company.

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6 Sources: Internal notes of SABRE Technology Solution, ROTATIONS (Flight Scheduling Journal by SABRE), Handbook of Airline Marketing, and Handbook of Airline Economics.
Figure 1.3: Planning process of airline schedule development
One of the most important and the latest event in the area of strategic decisions made by an airline is a strategic alliance with other airlines to position them globally and to gain advantages in many areas of operations, such as marketing, through economies of scale and economies of scope without investing too much additional capital or expansion of each member's routes. The global strategic alliance with other airlines, whether they are domestic commuter carriers, domestic majors, or international carriers, has almost become a necessity for every airline to survive in today's global and highly competitive environment. The strategic alliance has been adopted as a tool by many airlines to expand their network system without actually creating flight services to new markets. In today's highly competitive airline industry, entering a new market can be a very risky and costly business. However, the strategic alliance was able to provide participating partner carriers with means to reduce some of the risks involved with expanding operations and route network system. The most important and common feature of the strategic alliance is known as a codesharing agreement. A codesharing agreement allows one airline to channel its passengers into network's of the other carriers by mutual agreement between cooperating carriers, and at least one of the airline designator codes used on a flight is different from that of the airline operating the flight. Depending on the type of an alliance, the alliance can be formed between two airlines such as the one between Austrian Airlines and Delta Airlines or among multi-airlines such as the Star Alliance among United Airlines, Lufthansa, Air Canada, SAS, Thai, and VARIG. Codesharing has become the keystone of many strategic marketing alliances, and has received both praise and abuse by creating on-going debates whether codesharing actually benefits the

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7 Technical definition provided by the U.S. Department of Transportation.
flying public or not. One can claim that airlines are trying to fool passengers by providing misconceptions about their flights’ actual operators. For example, United Airlines can advertise and sell the seats that are actually flown by Lufthansa of Germany from Chicago to Frankfurt. Another point of view is that flying public can actually benefit from various types of strategic alliances by enjoying more choices in traveling options. However, since the details of a strategic alliance are beyond the realm of this research, only the concept of the strategic alliance were applied to the system.

As shown in Figure 1.3, once an airline has performed long-range market planning, the airline has to shift its focus to an operational planning process. At this stage, the airline has to decide the geographical coverage of its operations and this decision must be coupled with a long-term fleet planning process because the decision whether to operate only domestic flights or expand services to international cities will greatly affect the types of aircraft fleet the airline has to acquire. The decision to move forward to international market is very critical in terms of the future survivability of an airline. For example, a decision made by America West Airlines to fly to Japan forced the airline to file a chapter 11 bankruptcy in June 1991 even though it survived as a low-cost carrier to serve several niche markets by scaling back its operations to mainly domestic services. The importance of good long-term future fleet planning could be well explained by the history of the airline industry between 1993 and 1996 when the airline industry lost billions of dollars due to the miscalculation of long-term passenger traffic that had led to excessive fleet acquisitions.

Once all the strategic decisions are made, an airline has to start mid-term scheduling process by determining markets to serve, type of flight services (nonstop,
multi-stop direct, intraline connection, or interline connection), and flight frequencies between each city pair. During this process, an initial fleet assignment has to be performed to assign right aircraft types to all the flights and to generate a feasible aircraft rotation plan with an accurate aircraft count to avoid any deadheading of aircraft at certain airports during a given scheduling cycle. This can be achieved by ensuring that inbound and outbound flights at each airport are balanced. This mid-term scheduling process should begin as early as one year prior to actual scheduling period. It is also important at this stage to finalize and verify all the details that are related to strategic alliance and codesharing agreements with other airlines.

Once an airline accomplishes all the necessary planning processes, the airline is now ready to generate an initial schedule by incorporating all the specific operational constraints, such as airport related-requirements (curfew, ground handling equipment, ticket and gate counters and agencies, etc.), both cockpit and cabin crew requirements, and aircraft-related requirements (maintenance schedules). The initial schedule generation process also requires the fine-tuning of operational plans developed during the mid-term operational strategic process and transmission of the initial schedule to other operational departments within the airline, such as systems operations, crew scheduling, and maintenance, to allocate resources properly without any conflicts. Therefore, the main objective of this scheduling process should be to produce a feasible and routable schedule by minimizing operating costs.

After receiving feedback from other departments, the initial schedule can be revised by making minor adjustments to cure any conflicts and to provide better service for special peak demands, such as holidays and special events. Then, the final schedule
will be distributed not only within the airline, but also through several computer reservation systems (CRS’s), such as SABRE and Appolo, and global distribution systems (GDS) and to external agencies such as the Official Airline Guide (OAG). Once the schedule has been published for the flying public, the airline has to keep monitoring booking levels until the last minute of actual departure time based not only on individual flight segments, but also on true origin-destination markets to adjust fares, to a limited extent, change aircraft type, and cancel or add flights. Once the published flight schedule takes off, the airline will perform post-departure analysis to collect and study traffic, revenue, and cost data, which will be used for future enhancement.

Figure 1.4 shows the overall flow of the planning process of airline marketing once the scheduling is completed by following the procedures illustrated in Figure 1.3. Once the schedule is generated, pricing establishes the airline’s tariff structure. Even though it was mentioned that a reservation of a seat on an airplane is a basic product for an airline, schedule and pricing together define the airline’s final product.

![Figure 1.4 Process Flow in Airline Planning and Marketing](image)

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8 Sources: Ch. 10: Airline Planning and Marketing Decision Support, Handbook of Airline Marketing.
Once the final product is designed, yield management determines the quantity of each product to offer for sale. In other words, the airline will determine how many seats will be allocated for different buckets of fare classes and what types of restrictions will be placed for each fare bucket (for example, a 14-day advance purchase and Saturday night stay-over). Finally, each airline puts its products on the shelf for sale through several different distribution channels such as traditional travel agency, the airline itself, and the fastest growing various internet web sites. Even though information technology is revolutionizing airline operations at almost every level, perhaps the most recent exciting revolution may be use of the “internet” to distribute airline products (i.e., seats) to customers. Using this new distribution channel, airlines can not only sell their regular seats that can also be sold through traditional distribution channels, but also reduce spoilage of seats by offering either the last minute (usually offered through each airline’s web site for an upcoming weekend) or auctions (e.g., Priceline.com) for those seats that otherwise would go empty. Table 1.2 illustrates the increasing popularity of this new distribution channel. Since the details of this new revolutionary distribution channel are beyond the realm of this research, only a brief description has been discussed here.

<table>
<thead>
<tr>
<th>Web sites</th>
<th>June 1999</th>
<th>June 1998</th>
<th>% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS' Expedia.com</td>
<td>4,203</td>
<td>2,145</td>
<td>95.9%</td>
</tr>
<tr>
<td>Sabre's Travelocity.com</td>
<td>4,118</td>
<td>2,093</td>
<td>96.8%</td>
</tr>
<tr>
<td>Priceline.com</td>
<td>2,012</td>
<td>896</td>
<td>124.6%</td>
</tr>
<tr>
<td>American Airlines</td>
<td>1,530</td>
<td>1,304</td>
<td>17.3%</td>
</tr>
<tr>
<td>United Airlines</td>
<td>1,250</td>
<td>640</td>
<td>95.3%</td>
</tr>
<tr>
<td>Delta Airlines</td>
<td>1,152</td>
<td>1,093</td>
<td>5.4%</td>
</tr>
<tr>
<td>Southwest Airlines</td>
<td>1,151</td>
<td>315</td>
<td>265.4%</td>
</tr>
</tbody>
</table>

(Source: Media Metrix)

*Table 1.2: Internet airline bookings (in thousands)*
1.3.2 Airline Productivity Measures

To determine whether it is marketing its product efficiently and profitably, a company or a specific industry must define productivity measures. Different industries, or even different companies in the same industry, might have different definitions of productivity measures. This section will examine some of the characteristics of airline economics and the basic definitions of airline productivity measures. As discussed in the previous section (Scope of the Research and Global Assumptions), only the passenger traffic will be considered when discussing the economics of airlines and airline productivity measures.

Productivity of any company can be defined as the ratio of output to input. In the case of passenger airlines, output can be measured by the number of passengers carried and the revenues generated by carrying those passengers. The most basic and important revenue indicator for an airline industry is called a passenger yield which can be defined as the revenue generated by carrying one passenger for the distance of one mile. It is expressed in cents per mile and computed as follows:

\[
\text{Airline Passenger Yield} = \frac{\text{Revenue (or Fare)}}{\text{Revenue Passenger Miles (RPMs)}}
\]

The concept of yield is very similar to the term called unit price that applies to other industries. For example, eggs are usually priced and sold by the dozen at a grocery store and it is very rare that anyone is buying just one egg. If we assume that a dozen of eggs costs $1.20, then the unit price of a single egg would be 10¢. In the same way, when an airline is quoting a fare from one city to another, the fare always represents the total amount a passenger has to pay to cover the entire trip from his/her origin to destination. However, the yield represents the fraction of that fare for the passenger to travel one mile.
between the same origin and destination. For example, if we assume that a one-way fare from Columbus to Los Angeles is $200 and the distance flown is 2000 miles, then a passenger yield is 10¢ per mile from CMH to LAX\(^9\). This 10¢ represents the amount a passenger has to pay to fly one mile from CMH to LAX.

\[ \text{Yield} = \frac{\$200}{2000 \text{ miles}} = 0.1 = 10\% \]

\( \ast \) Break-even load factor (B.E.L.F.) is the percentage of the seats the airline has in service that it must sell at a given yield, or fare level, to cover its total costs.

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*Figure 1.5: Elements related to Airline Productivity Measures*
Input for the airline industry consists of the resources employed in the production of the capacity needed to carry the traffic. Some of these resources could be labor, such as cockpit and cabin crews, capital assets, fleet of aircraft, and any other purchased goods and services. Therefore, airline productivity can be basically expressed as a ratio of a generated traffic to either labor resources or aircraft assets.

Airline productivity measures in terms of aircraft should be examined based on the notion that the basic productive assets of an airline are individual airplanes. Then, each airplane can be treated as a separate factory. An airline can be then an entity that is composed of several of these factories, which constitute the airline’s fleet with various types of aircraft to fly different types of market – long-haul versus short-haul, low-density versus high-density. The productive output of each factory is the traffic the airplane carries as measured in terms of revenue passenger miles (RPM) which is the denominator of the definition of yield. The input which is used as a denominator in the productivity ratio is the aircraft itself. The aircraft used as an input to determine airline productivity can contain not only the capital cost of its acquisition, but also the labor (crew) cost and purchased goods and services such as fuel and maintenance. Figure 1.5 illustrates the relationships among the elements that need to be analyzed to measure airline productivity.

1.4 Research Organization

This dissertation focuses on the development of a user-friendly, computerized airline scheduling system which enables both planning and evaluation of each schedule created. The system incorporates comprehensive and integrated algorithms and models that constitute a basic platform, the core engine of the system. Therefore, this
dissertation includes some chapters that are dedicated to the development of the algorithms and models and other chapters that are dedicated to the development of the actual computerized scheduling system.

The first chapter of the dissertation introduces the objectives and motivations of the research and addresses the scope of the research, including the global assumptions that had to be determined before developing a manageable, but very realistic system. The chapter goes on to describe the background information of airline scheduling procedures and the theory behind the measurement of airline productivity which can be applied to determine the effectiveness of the airline schedule generated. Chapter 2 reviews the literature relevant to the research. The areas covered in this comprehensive literature review include airline scheduling problems, airline route network systems, fleet assignment problems, market share analysis, and traffic allocation systems.

Chapter 3 relates to the development of the algorithms and models that are incorporated in the computerized system. This chapter illustrates the overall structure of the airline scheduling system by showing the relationships among different modules implemented in the system. Then, it discusses some of the definitions and concepts related to airline scheduling. Chapter 4 and Chapter 5 present the theories and models implemented in the flight schedule generation system and the flight schedule evaluation system. These two chapters discuss in detail the procedures for developing the necessary models and the computer system as a whole.

Chapter 6 summarizes and reiterates the dissertation's contributions to both the academic field and the actual airline industry by discussing the unique advantages and benefits of the developed system that both academicians and airline practitioners can
appreciate. This chapter also suggests possible areas in the system that could be improved with more research. Chapter 6 is then followed by an extensive bibliography.
CHAPTER 2

LITERATURE REVIEW

As mentioned in Chapter 1, operations research professionals both within and outside of airlines have been working on the development of methods for obtaining optimal schedules since the 1950s [44]. The work has been discussed extensively in the symposia of AGIFORS (Airline Group of the International Federation of Operational Research Societies). Even though some of the work has been published in the Proceedings of AGIFORS which is relatively difficult to access, most of the work has been kept and documented in airlines’ internal reports.

One of the contribution of this dissertation is in the comprehensive review of literatures on the subjects of airline scheduling problems, airline route network system, fleet assignment and aircraft rotation planning, airline market share analysis, and airline passenger allocation. This chapter provides a comprehensive survey of research on these areas that serve as the framework of the developed computerized airline scheduling system.
2.1 The Airline Scheduling Problems

2.1.1 Airline Schedule Development

Since deregulation, U.S. airlines have been free to serve whatever domestic markets they want, and they adjust their schedules often in response to market opportunities and competitive pressures. Along with price, schedule is the most important consideration for air travelers. For business travelers, schedule is often more important than price. Business travelers like to see alternative flights they may take on the same airline if, for instance, a meeting runs longer, or shorter, than they anticipate. A carrier that has several flights a day between two cities often has a competitive advantage over carriers that serve the market less frequently, or less directly. According to Etschmaier and Mathaisel [44], the flight schedule is a central element of the commercial airline planning process. The schedule defines not only the product but to a large extent also the production plan. Since a significant part of airline costs and revenues are fixed for any developed flight schedule, optimization of the flight schedule is critical to finding the most efficient and effective deployment of an airline's resources.

Airlines establish their schedules in accordance with their marketing objectives. However, schedulers also must take into account aircraft and crew availability, maintenance needs, and airport operating restrictions. Many airports around the world have established curfews and other limitations of aircraft operations in response to complaints from surrounding communities about noise. Scheduling flights at busy international airport is becoming more and more of a juggling act [83]. Schedulers of
longhaul flights have to deal with limitations imposed by scheduling windows\textsuperscript{10}, limitations imposed by airline, and crew operational/logistical requirements and at the same time keep the marketing department happy with flight times that are both friendly to the passenger and maximize potential transfer [5]. Therefore, when an airline is scheduling a flight, it has to consider not only the factors that the airline can control, such as aircraft/crew resources and connecting complex\textsuperscript{11} at hub airports, but also the factors that are out of the airline’s control, such as curfews at airports, availability of customs, immigration, and quarantine (CIQ) facilities, and certain characteristics that are related to geographic location of a particular airport such as proximity of airport to the center of the city and time difference from GMT (Greenwich Mean Time) [56]. For example, India’s international terminals really come alive in the middle of the night, between the hours of 00:30 and 5:30 when most international airports are either closed or handling a minimal number of passenger flights, and they are fully geared up for such an operation [6]. This anomaly is at least partly due to India’s geographic location, five-and-a-half hours time difference east of GMT.

\textsuperscript{10} Scheduling window is the period of time frame of the day (24 hours) an airline can schedule for departure and arrival times for their flights. The scheduling window varies by elapsed clock time (ECT) which is the time difference between local arrival time and local departure time, taking into consideration both time zone changes and flight’s block time (i.e. ECT = flying time + time zone change). For example, assuming that there is a curfew at the destination airport between 11:00 p.m. and 6:00 a.m., then a flight with ECT of 10 hours can depart only between 8:00 a.m. and 11:00 a.m. so that the flight can arrive at the destination airport during the non-curfew hours. In this example, if the flight departs at 9:00 a.m., then it will arrive at the destination airport at 19:00 (7:00 p.m.).

\textsuperscript{11} Connecting complex is the combination of arrival bank of inbound flights and departure bank of outbound flights at hub airports, which can provide connecting services to passengers.
Since 1950s, numerous models have been developed to design airline schedules. Different operations methods, objective functions, and operational constraints have been applied when modeling airline schedules depending on the approach to the design. Whenever different approaches were made, most up-to-date computer techniques available at the time were employed due to complex and combinatorial nature of the problem. The most basic and fundamental approach to airline scheduling problems has been to formulate the objective function with given constraints and solve the problem by a standard optimization algorithm. A typical objective function would be to find a set of flights, with associated assignment of aircraft and departure and arrival times, which can:

1) maximize profits by either maximizing traffic revenues or minimizing direct and indirect operating costs;

2) maximize the number of revenue passenger miles (RPMs)/revenue ton miles (RTMs); and

3) minimizing the number of aircraft in operation.

These objective functions are formulated into mathematical models with given constraints. Some of these constraints can be a set of demand functions and associated revenues for every passenger origin-destination market over the time-of-the-day of scheduling cycle, route characteristics, operating restrictions, and fleet composition, such as types of available aircraft and the number of aircraft in the [70]. These modeling efforts were essentially an extension of the formulation by Dantzig [29].

Since 1970s, it has been recognized that the airline scheduling problem is best solved through a structured planning process in which all parts of the airline participate. An airline's scheduling department develops a draft schedule which is evaluated by the
various operating departments in terms of feasibility and profitability. Once the scheduling department receives feedback from the various departments, an updated schedule is prepared and this iterative process is repeated to achieve a near-optimal flight schedule is generated. Even though there exist some significant differences in this airline scheduling process among different airlines, most airlines today either explicitly or implicitly implemented a similar scheduling system which is basically composed of two phases: schedule construction and schedule evaluation.

Etschmaier and Mathaisel [44] review the development and construction of the airline schedule, discuss methods to evaluate the schedule, and finally present some directions for future work in the area of airline scheduling. The relationships between the different functions within the airline and the development and execution of the schedule are also covered. As noted by Etschmaier and Mathaisel, there are two basic airline schedule designing (schedule construction) methodologies: direct approach and step-by-step approach. In the direct approach to airline schedule design, various heuristic procedures are employed for preparing a schedule by sequentially selecting flights and making minor changes if necessary in flights previously chosen. Most of those models have adopted interactive computer programs and these approaches are cited in the following literatures: [32], [41], [67] [89], [90], [91], [139], and [163].

The step-by-step (stepwise) approaches commence by selecting routes which are to be served and determining the frequency of service on each route. This first step is called frequency planning or frequency optimization as defined in the following literatures: [20], [29], [40], [43], [61], [62], [95], [96],[97], [112], [113] [114], [115], [127], [128], [137], [148], [149], [150], [152], and [155]. In the second step of this
approach, possible departure times are determined taking into consideration both the
time-of-the-day variability of passenger demand and the possible connections to other
flights of not only their own airline (intraline connection), but also other airline (interline
connection) in order to allow passengers to continue their trips with minimal connecting
times. This second step has been studied by a number of researchers [10] [11] [20] [37]
[50] [51] [70] [76] [82] [96] [100] [101] [112] [133].

The next step involves the testing of the proposed flight schedule in terms of
operational constraints and the development of an aircraft rotation plan. Aircraft rotation
plans are developed to determine the number of aircraft required for executing the
schedule, and changes are identified which could lead to a reduction of the number of
aircraft required. Some works on aircraft rotation plans are cited in [11], [12], [15], [19],
[26], [31], [37], [57], [77], [79], [84coletti], [91], [97], [108], [120], [121], [123], [140],
[147], [165], and [168].

These two approaches, direct approach and step-by-step approach, illustrated here
are the methods studied in terms of airline schedule construction. Schedule construction
takes into consideration only factors of primary importance such as: passengers as
represented through some simplified demand function; aircraft with their operating
characteristics, including some simplified cost function; geography of the route network;
a simplified representation of authorization and commitment to serve routes; and in some
cases, the expected behavior of the competition.

2.1.2 Airline Schedule Evaluation

Once the schedule is developed, the airline must have a system that should be able
to evaluate the schedule to achieve near-optimal airline flight schedule and this procedure
is called airline schedule evaluation. The objective of the schedule evaluation is to estimate with some accuracy the costs that will be incurred and the revenues that will accrue from flying the proposed schedule [44]. Evaluation of the schedule can be performed in terms of several factors, such as flight punctuality, cockpit and cabin crews, ground crews and ground facilities, aircraft maintenance equipment, and so on. ([10] [35] [43] [64] [109] [131])

Market share models are used in forecasting airline passenger demand in an origin and destination (O&D) market for an individual flight based on its relative attractiveness with respect to other competing flights [248] [255] [256] [260]. In conjunction with market size calculations, market share forecasts can be used to predict passenger demand for individual flights and hence their profitability. The ability to accurately forecast market share is a critical part of identifying a profitable flight schedule [293]. Market share models intend to model the choice process of airline passengers. One standard approach is to develop an attractiveness, or Quality of Service Index (QSI) score and express the market share of an individual flight as its QSI score divided by the sum of all other QSI scores in the O&D market. This QSI method was first developed by the staff of Civil Aeronautics Board (CAB) for application in domestic-route proceedings (such as the investigation of Reno-Portland/Seattle nonstop service, May 1970) and, over a period of years, has gained acceptance by the airline industry and government agencies. It is also being used in the internal planning processes of the carriers for analyzing the profitability of alternative new routes and for assessing possible merger partners. The method assigns standard weights to some of attributes that are related to each flight itinerary. Typical variables considered by most market share models include type of
flight service (nonstop, through flight, or connecting service), time-of-day preferences, displacement time (time between preferred and actual departure times), elapsed time for the total passenger journey, aircraft types, airline images, and available fares [251] [252].

Even though this still is the most widely used method in the airline industry, a term, Quality, in QSI does not imply the meanings of airline quality that are perceived by most flying public.

Passenger spill can be defined as unaccommodated passenger demand that results from capacity restrictions [293]. Since much of flight scheduling is concerned with matching aircraft capacity with passenger demand, the estimation of passenger spill is an important part of forecasting the profitability of a proposed flight schedule [265]. Once passenger spill has been estimated, it is often useful to then estimate the mix of passengers that have been recaptured, that is, accommodated on other flights.

Teodorovic and Krcmar-Nozic [155] propose a method for determining flight frequency on routes in order to achieve the best possible results with existing transportation capacities in a competitive market. They argued that the problem of determining flight frequencies on a route network is a large combinatorial problem whose optimal solution is difficult to find, and a heuristic approach must therefore be used to solve it. They solved the nonlinear problem of determining flight frequency using the Monte Carlo technique which randomly generates solutions whose feasibility is examined. The process was repeated several times and the best solution was taken as an approximation of the optimum. The paper also discussed the model that shows the functional relationship between market share and frequency share.
\[ MS_{ip} = N_{ip}^\alpha + \sum_{j \neq i}^m N_j^\alpha \]

where: 
- \( MS_{ip} \) = market share for airline \( p \) on route \( i \),
- \( N_{ip} \) = flight frequency of carrier \( p \) on route \( i \),
- \( m \) = number of competitive carriers flying on route \( i \),
- \( \alpha \) = empirically obtained constant (range: \( 1 < \alpha < 2 \))

Miller [100] develops an aircraft scheduling model that accounts for consumer preferences, costs and other constraints. Miller’s model is only for one city pair but examines the economic welfare aspects of different scheduling schemes and suggests a feasible airline schedule for the single city pair. Miller brings together the engineering aspects of schedule development with the primary economic issues. Similarly, Dobson and Lederer [37] develop a model that maximizes an airline’s profit based on the existing schedules of competing airlines. Their work identifies optimal prices and schedules for the airline and calculates demand for each of its routes based on service quality and price. Their formulation, which is highly nonlinear, only presents a solution for one market, not an entire airline system. The solution algorithm found the best flights, routes, and prices in a three level hierarchical process. The third level which is the lowest, finds optimal route prices that satisfy capacity constraints and consumer choice behavior. This algorithm also determines the airline’s total revenue for a single route. Lastly, the research examines competition among airlines and searches for an equilibrium among carriers.

The importance of an automatic flight schedule construction and evaluation systems has been emphasized in many literatures. American Airlines SABRE group has emphasized that the complex challenges airlines face today require scheduling tools that are more advanced and more sophisticated but more user-friendly than ever [125] [126].
Many airline scheduling routines used by the major airlines have become PC-based systems. It also has been mentioned in several articles that it is extremely difficult, not impossible, to achieve perfectly optimized airline schedules and operations mainly because there are so many variables involved up to the last minute of flight departures and the conclusion of each flight (en-route and arrival at the gate). The literature survey on airline scheduling problems has reinforced the need for and importance of this dissertation.

2.2 Airline Fleet Assignment and Aircraft Routing

After creating a flight schedule, the airline must decide what equipment type, or fleet type, should be assigned to each flight and which specific aircraft, or tail number, of each aircraft type should fly each flight leg or sequence of flights so each aircraft visits maintenance stations on a regular basis. These problems are referred to as the fleet assignment problem and aircraft rotation (routing) problem, respectively [1] [2] [31]. Another problem the airline has to consider in aircraft scheduling is to decide which sequences of flights should be assigned the same aircraft (identical tail number) and this is referred as the through flight assignment problem [151]. Through flight is defined as the flight, using the same flight number and the same aircraft, that serves two airports with one or multi-stops en-route, but requires no change in aircraft. Assigning the proper through flights can improve the revenues by providing better itineraries to high density markets, where there are not, however, enough traffic demands to justify nonstop flight services, then connections that require changes in aircraft at hub airports [11]. Wollmer presented a tail routing algorithm that meets a flight schedule with a minimum number of aircraft [165]. He also suggested a possible solution as an extension to his work in case
of deadheading in aircraft routing. The solution he suggested was to establish service on
the deadhead segments in order to generate additional revenue and to balance the flow of
an aircraft movement that will be discussed in great detail in Chapter 4.

According to Abara [2], the goal of the fleet assignment problem is to generate an
assignment of fleets to flights, that satisfies certain constraints. Abara [2] and Daskin and
Panayatopoulos [30] presented solutions to the aircraft fleet assignment problem. These
authors begin with a schedule that has already been set but in which the physical
assignment of aircraft has not. Abara applies integer linear programming to the problem
and permits the assignment of two or more fleet types to the flight schedule. Daskin and
Panayatopoulos use Lagrangian relaxation to assign aircraft to routes within a hub and
spoke network with the objective of maximizing profit. The main input for the fleet
assignment problem is a weekly schedule or flight legs. The output of the fleet
assignment model is an assignment of fleet to flights that either maximizes revenues or
minimizes operating cost [63]. The assignment also has to satisfy some constraints [34].
First of all, each flight must be assigned to exactly one aircraft. Then, for each aircraft
type and for all the airports in an airline’s route network, the number of aircraft departing
from an airport must be equal to the number of aircraft arriving at the airport. This
requirement ensures the continuity of aircraft at each airport. Lastly, the number of
aircraft used must not exceed the number available.

Levin [89] examines the fleet assignment problem with both fixed and variable
schedules. The fixed schedule is one that cannot be changed while a variable schedule
permits changes to arrival and departure times; the variable schedule permits the airline
to respond to changes in demand. By identifying the minimal fleet for the variable
demand case, the airline can determine what effect minor changes on the schedule can have on its fleet requirements. Mathaisel [96] examines the assignment of aircraft to routes under variable demand while including market price and level of service. In his model, price, capacity, and demand are all variables, which lead to a nonlinear functions. Mathaisel splits the revenue-maximizing objective function into two criteria to account for the nonlinearity. The first objective function maximizes the passenger traffic carried and the second one maximizes the fares. He employed a goal programming approach to solve these objective functions.

Soumis and Ferland [139] adapted the Frank-Wolfe algorithm to solve a large-scale aircraft routing and scheduling problem. Their model accounts for the differences in passenger satisfaction that occur with changes in the schedule and attempts to maximize both company profits and passenger satisfaction. The model alternately solves an aircraft routing problem and a passenger assignment problem. The latter problem permits the model to estimate profits. By making changes to the aircraft routing problem and noting changes in profitability, a solution that maximizes profitability and satisfactions is identified.

According to Talluri and Gopalan [151], the through flight assignment problem rises to construct a set of itineraries that maximizes through revenues. Since through revenues are represented by a complex nonlinear relationships, the modeling of this problem can be quite involved. Therefore, most earlier work has relied on heuristics [11]. Talluri and Gopalan developed a through assignment model as a simple set packing problem. They calculate the increase in revenues for a through assignment using traffic forecasts for the market, the average revenue of passengers in that market, and the
desirability of that through flight as compared to the desirability of other itineraries serving the same market. The desirability of a through depends on a number of factors such as number of stops, circuity of the through, etc.

The fleet assignment solution assigns fleet types, not specific planes, to flight legs. Aircraft rotation problems, actual assignment of specific aircraft, or tail numbers, to the fleeted schedules, determine a set of aircraft routing plan that satisfy the similar requirements illustrated above for fleet assignment. However, there is an additional constraint for the aircraft rotation problem, which is maintenance regulations set by the Federal Aviation Administration (FAA). In order to ensure air travel safety, the FAA requires airlines to perform four types of aircraft maintenance called A, B, C, and D checks [47] [151]. FAA requirements prohibit an aircraft to fly unless appropriate maintenance checks are performed within specified periods. Table 2.1 describes these maintenance checks.

<table>
<thead>
<tr>
<th>Type of Check</th>
<th>Works</th>
<th>Frequency</th>
<th>Labor Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periodic service</td>
<td>Minor visual inspection</td>
<td>Between flights (during downtime) or overnight</td>
<td>2 man-hours</td>
</tr>
<tr>
<td>A-Checks</td>
<td>Routine maintenance</td>
<td>Every 65 flight hours (= once a week)</td>
<td>10-20 man-hours</td>
</tr>
<tr>
<td>B-Checks</td>
<td>Thorough visual inspection + lubrication of all moving parts</td>
<td>Every 300 to 600 flight hours (= once a month)</td>
<td>Narrow-body (NB): 100 man-hours; Wide-body (WB): 200 to 300 man-hours</td>
</tr>
<tr>
<td>C-Checks (for NB only)</td>
<td>Taken out of service</td>
<td>Once every year</td>
<td>2,100 man-hours; 3 days to complete</td>
</tr>
<tr>
<td>D-checks (heavy C-checks)</td>
<td>Taken out of service; Complete over-haul</td>
<td>NB: once every 4 C-checks</td>
<td>20,000-30,000 man-hours; 3-5 weeks to complete</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WB: once every 15-18 months</td>
<td>10,000 man-hours; 2 weeks to complete</td>
</tr>
</tbody>
</table>

(Source: American Airlines web site: http://www.amrcorp.com/corpcts.htm)

Table 2.1: A typical aircraft maintenance procedure
2.3 Airline Route Network System

The practice of hubbing in the U.S. air transportation system has been on the rise since airline deregulation, and hub-and-spoke scheduling became the prevailing method used to route aircraft and passengers of the major U.S. scheduled carriers to achieve higher use levels and load factors. In other words, airlines have altered their route structures to utilize their resources more efficiently.

There have been many studies on the hub-and-spoke system in the airline industry. While most of the studies have proved the needs of the hub-and-spoke system in this very competitive industry, most of them have also listed the possible disadvantages of the hub-and-spoke system. From the operation's standpoint [323], peaking of arrivals and departures, an inherent characteristic of hub-and-spoke systems, has contributed to the congestion of airports and airways and created a need for additional facilities to handle a large volume of traffic for short period of time. From the passengers' standpoint, trip times in some markets have increased, because they have involved a stop or a change of plane at the hub. According to O'Kelly and Miller, the most notable advantages of the hub networks are stated in [201] that these configurations reduce and simplify network construction costs, centralize commodity handling and sorting, and allow carriers to take advantage of scale of economies through consolidation of flows. There also have been numerous studies on the hub-and-spoke system in terms of its effect on airline profitability, changes in passenger enplanements, fares and service frequency [188] [210] [186] [179] [184] [203] [176] [190].

The benefits of economies of scale (size), economies of scope, economies of size, or economies of density can be achieved through the market dominance. One
consequence of hubbing in the airline industry has been growing dominance of major carriers at their hub airports. The issues associated with hub dominance have been examined in several studies. For example, Levine [307], Bailey, and Williams [290] described the role of airport dominance, along with economies of scope and scale, in generating rents to air carriers. They contend that in recent years the tendency toward hub dominance has blocked further competition in local hub markets, for example, by locking up available gate space in long-term lease arrangements and distorting local travel agency incentives. Financial analysts and others assessing airline profit strategies have also concluded that airlines use hubs to shield some of their output from competition [202]. Some airport leases give the incumbent airline exclusive use of the facilities it is helping to finance, even if it is not using them. When a new entrant wishes to serve such an airport, it must sublease facilities from the incumbent airline. If the new entrant is a potential competitor, the incumbent is in a position to extract monopoly rents.

The study done by Kanafani and Ghobrial [292] has provided some of the aspects on the future structure of the airport system, and suggested that network hubbing will persist as an important feature of air transportation, but in a multi-hub system. The study indicated that the future of airport system networks depends upon such factors as:

1) traffic growth between different cities;

2) increased congestion delay at hubs which may drive airlines to move some of their operations to less congested hubs;

3) introduction of new large aircraft to use existing runways and gates without further drastic expansions and
4) implementation of some hub pricing policies and slot allocation among airlines using large hubs.

Their approach to network planning is based on the assumption that conditions of equilibrium in air travel markets follow those of monopolistic markets. They have used this equilibrium model to project the air network structure that is predicted to be an extensive hub networks for the year 2000, using an annual compound growth rate of 6%.

The summary of output statistics is shown in Table 2.2. Table 2.2 shows that both flying costs and direct operating costs are relatively unchanged, while the average congestion cost per passenger appears to increase significantly.

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>1986</th>
<th>2000</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systemwide average flying cost per pax.</td>
<td>40.51</td>
<td>39.30</td>
<td>-2.99</td>
</tr>
<tr>
<td>Systemwide average congestion cost per pax.</td>
<td>3.87</td>
<td>6.82</td>
<td>76.23</td>
</tr>
<tr>
<td>Average systemwide direct operating cost per pax.</td>
<td>43.20</td>
<td>46.12</td>
<td>6.76</td>
</tr>
</tbody>
</table>

Table 2.2: A Summary of Output Statistics of the Equilibrium Model

Kanafani and Ghobrial [190] also argued that the forces that encourage airline hubbing are primarily a function of aircraft technology, influenced by market considerations such as frequency competition and airline presence at major airports. For example, if it were possible for airlines to operate economically with single-seat aircraft, then all passengers could be served directly between their points of origin and destination. There would be no need for passengers to transfer, and hubbing would not exist. However, as soon as aircraft size begins to offer economies of scale and to dictate a schedule, larger traffic volumes to and from large cities in a region encourage the use of larger aircraft. Thus, airlines need to fill the aircraft flying to and from the hub airport and to reduce the non-stop service between spoke cities. This consolidation of passengers in links to and from the hub allows airlines to capitalize on the economies of
aircraft size. Consolidation also allows both airlines and passengers to take advantage of the economies of increased schedule frequency.

In the earlier study also done by Kanafani and Ghobrial [191], they paid particular attention to the importance of the interaction that occurs between aircraft characteristics and network structure. For example, the extent to which hubbing will occur depends on the economies of scale that can be achieved by aggregating traffic volumes through a single hub: such economies are likely to be more significant with larger aircraft than with smaller ones. As discussed by Kanafani and Ghobrial in the studies [190] and [191], larger aircraft that could provide benefits of economies of size to airlines may be scheduled into congested hubs. Because of the extra seating capacity, more passengers can be served without adding flights and congestion and this will reduce unit operating costs per available seat miles.

In Nicol's study [272], unit direct operating cost (DOC) tends to decline with increasing aircraft size. His analysis has emphasized the importance of the stage length parameter in determining the level of the cost function, and the importance of utilization (e.g. annual departures per aircraft) in determining output and thus cost. Of further interest and importance, however, is the finding that the underlying components of DOC do not tend to behave uniformly with aircraft size. Unit capital costs, insurance plus other costs, and landing fees actually increased with aircraft size, while unit crew, fuel, and maintenance costs essentially decreased. It is interesting to note that the latter factors of DOC (unit crew, fuel, and maintenance costs) mentioned above can be related to the savings that could result from the market dominance by an airline. Therefore, this result is somewhat related to hub dominance theories discussed earlier. Goodovitch [184],
however, argued that the hub-and-spoke system can only benefit from cost-efficient operations of large aircraft to a certain limit.

Weidner [209] argued that operating larger aircraft reduces operating costs per seat-mile and thus cost per passenger. The study also states that using any of the service options to accommodate the higher link flows of the hubbed network reduces the airline's operating costs per passenger and may allow the carrier to attract additional traffic. This property of reducing unit (per passenger) costs with increased output (link flows or traffic density) is termed link economies of scale or economies of density and is the primary motivation for operating a hubbed network structure.

In a study which used somewhat different approach in examining the effects of the hub-and-spoke system by studying alternatives to the hub operations, Schwieterman and Spencer [204] explained that hub-and-spoke operations permit manpower to be scheduled on efficient lines-of-flying from central locations, and allow more efficient planning for pilot and flight attendant reserve coverage. They also argued that hub operations can reduce seat-mile costs by 10 percent or more.
CHAPTER 3

AIRLINE SCHEDULING SYSTEM FORMULATIONS AND STRUCTURES

The objective of a good schedule, from the airline’s point of view, is to provide a proper flight frequency that can generate a near optimal load factor which will maximize the airline’s operating profits within the constraints of competition, regulations, equipment, and environment. Maximizing the number of revenue passenger miles (RPMs), passengers, or revenues, and minimizing the total operating costs of an airline would be the logical criteria of a good airline schedule. In addition to these criteria, passenger preference – based local departure and arrival times, the block time of an aircraft, the type of an aircraft, etc – for any given flight also influences airline scheduling. Together, these factors and criteria are the elements of objective functions and constraints of various airline scheduling problems.

A complete airline schedule is a working obligation for all those employed in the air carrier services. Both the carrier’s economic results and the quality of services offered to passengers depend mainly on how the airline schedule is developed and executed. Therefore, an airline’s major goal should be to achieve a profitable and reliable flight schedule to sustain long-term profitability. As emphasized in the previous two chapters, the output of an airline is the schedule of services it offers to the traveling public because airline scheduling determines where and when the airline will fly using
certain types of aircraft. The nature of the airline product is that it cannot be stored nor transported (perishable product) and the production facility (the aircraft) needs to change its location while production occurs. In other words, an empty seat on an airplane cannot be sold later and a possible revenue for that seat is lost for good. So the schedule must be designed to capture as much business as possible, maximizing revenues with as little direct operating cost as possible. The need for extremely accurate scheduling is further complicated by the fact that airline product production, which is a scheduled flight flying toward a destination, is only possible in batches and by the fact that patterns of traffic demand vary substantially over time. In this way, an airline business is faced with the capital-intensive quality of a manufacturing environment that is combined with the low-profit environment of retail sales. In addition to these characteristics of airline product and production plant, an airline also encounters political (such as bilateral agreements), economical (one of the most important factors, the state of national and world economy), social and environmental (such as noise restriction), and technological factors.

In this dynamic environment, where profits have historically been low and costs historically high, how well an airline plans and implements its schedule can very well determine its future. Since a small adjustment in the schedule may result in millions of dollars of additional revenue or in millions of dollars of losses, success of an airline mostly depend on the ability to operate flights along the schedule as efficiently as possible. All these problems create an immeasurably large set of scheduling decision variables, which, in turn, makes it impossible to formulate a unique objective function and achieve an optimal flight schedule. The airline thus becomes a very complicated system of interactions within itself and with the environment. Control of such a system
requires the development of a cybernetic model which essentially simulates all the
interactions of the systems. That need for control has increased the airline industry’s
needs of developing automated scheduling decision support tools.

The term “Airline Scheduling” has been applied to describe two distinct type of
interrelated activities [67]:

1) the development of a timetable of flights to meet a certain anticipated pattern of
   passenger demand, and;

2) the assignment or allocation of aircraft and/or crew fulfilling a given timetable.

Mathaisel [44] then divided the process of airline scheduling into two distinctive phases:
“airline schedule construction” and “airline schedule evaluation”. The four components
described in both Hersh [67] and Mathaisel [44] form the basis of the computer
scheduling system developed as the main part of this dissertation. Figure 3.1 illustrates
the detailed relationships among these components and their sub-components. This
diagram is based on the basic structure of a schedule development system, as illustrated
in Figure 1.1. To aid in the task of constructing an airline’s flight schedules and
evaluating the effect of interacting variables that are used to formulate airline scheduling
problems, not only have mathematical models and computer algorithms been developed,
but also a comprehensive computer system has been developed. The entire system is
intended to speed and simplify schedule development over manual methods. An
interactive decision computer system with comprehensive airline scheduling computer
algorithms and mathematical models embedded at the heart of the system can be used as
a tool to present scheduling information in a convenient format while still allowing for
quick and easy manipulation of the schedule. By increasing the speed of the scheduling
processes, more scheduling and rescheduling alternatives can be investigated at each scheduling stage. The use of computer systems can speed up the rate of evaluations so much that decisions can be made before a coalition is formed. The computer system developed for this dissertation provides an easy-to-use tool for solving sub-problems, evaluating and refining intermediate solutions, and controlling the order in which sub-problems are processed.

*Flight Schedule Generation System*

![Diagram of the airline schedule development system](image)

*Figure 3.1: Relationships among modules in the airline schedule development system*
The purpose of a schedule construction model is not simply to speed up the existing manual job of constructing feasible schedules: it is to provide a tool which permits the planner to quickly develop alternative feasible schedules and select the best. Therefore, the main objective of the schedule construction system is to generate the feasible flight schedules for a given route structure and passenger demand pattern. Naturally the ability to construct alternative schedules creates the need to evaluate schedules rapidly. By using a schedule evaluation system, effects and restrictions can be rapidly assessed when any changes in the developed schedule are made. This provides a tool that can be used for a sensitivity analysis.

As illustrated in Figure 3.1, the entire airline schedule development system is composed basically of three sub-systems: the flight schedule generator system, the flight schedule evaluation system, and the output reporting system. The flight schedule generation system is composed of a flight schedule construct module and a fleet assignment/aircraft route planning module. The schedule construction module generates the airline's direct flight schedules and assigns the proper aircraft to each of these direct flights. The system also generates the aircraft routing plan and determines the feasible number of aircraft needed to satisfy the proposed flight schedule. By performing the fleet assignment and aircraft routing plan, the system checks if the generated flight schedule is feasible. Once the direct flight schedule is completed, all the possible connecting paths are automatically generated to build connecting flights. The output (a complete timetable of an airline) is then fed to the industry-wide schedule database, where and the airline's complete flight schedule is processed in the flight schedule evaluation system. Here, the airline schedule can be assessed in terms of its attractiveness to potential customers, its
comparison to airline competitors, and its profitability. Each airline’s market share is
determined by all origin-destination city pairs, and passenger traffic is allocated to each
nonstop flight based on the attractiveness of the flight. Then, based on the output of
passenger allocation analysis, revenues associated with each flight segment, each aircraft,
each true origin-destination market, and the entire network are computed. A cost analysis
module determines operating costs needed to execute the developed schedule. In the
segment and network profitability analysis, the revenues and costs are calculated by the
revenue generator module and cost analysis module. This entire process is repeated until
a near-optimal or satisfactory schedule is achieved.

The remainder of this chapter will illustrate the overall structure of the airline
schedule development system by showing the relationships among different modules
implemented in the system. This chapter also discusses some of the definition and
concepts that are related to airline scheduling. Then, Chapter 4 and Chapter 5 will
discuss each of these modules in great detail by examining the scheduling operations
which are used to build and modify complete schedules. Despite the global assumptions
and limitations of this dissertation mentioned in Chapter 1, smaller scale of operating
constraints and assumptions that were actually applied to the airline scheduling system
will be discussed in these two chapters. These two chapters (Chapters 4 & 5) will also
present not only the models and algorithms that are fundamental frameworks of the
computerized airline scheduling system, but also the detailed structure of the airline
scheduling system.
3.1 Summary of System Components

Because of the complexity of different modules and subroutines implemented in
the airline schedule development system, an abbreviated name will be used when
referring to a certain module or subroutine. Table 3.1 lists all the abbreviated names of
the modules and subroutines, and the corresponding figure numbers show the detailed
algorithms of the modules and subroutines. The tree diagram in Figure 3.2 shows the
basic structure of these modules and subroutines, which illustrates how these components
are related to each other within the entire system. Figure 3.2 also shows a hierarchy of
the components that are implemented in the system. Each symbol shown in both Table
3.1 and Figure 3.2 indicates, with the last letter of the symbol, whether it is part of a
system, module, or subroutine. If a symbol ends with a letter "Y," it denotes a system. If
it ends with an "M," it represents a module. If the last is an "S," then the symbol denotes
a subroutine.

![Figure 3.2: Hierarchy of system components](image-url)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Component category</th>
<th>Full name</th>
<th>Corresponding figure #</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASDSY</td>
<td>System</td>
<td>Airline Schedule Development system</td>
<td>3.1</td>
</tr>
<tr>
<td>FSGSY</td>
<td>System</td>
<td>Flight Schedule Generation system</td>
<td>4.1</td>
</tr>
<tr>
<td>FSESY</td>
<td>System</td>
<td>Flight Evaluation system</td>
<td>5.1</td>
</tr>
<tr>
<td>DFSGM</td>
<td>Module</td>
<td>Direct Flight Schedule Generator module</td>
<td>4.2</td>
</tr>
<tr>
<td>ARM</td>
<td>Module</td>
<td>Aircraft Rotation module</td>
<td>4.7</td>
</tr>
<tr>
<td>CBM</td>
<td>Module</td>
<td>Connection Builder module</td>
<td>4.21</td>
</tr>
<tr>
<td>MSDM</td>
<td>Module</td>
<td>Market share determinant module</td>
<td>5.4</td>
</tr>
<tr>
<td>PAM</td>
<td>Module</td>
<td>Passenger allocation module</td>
<td>5.5</td>
</tr>
<tr>
<td>RGM</td>
<td>Module</td>
<td>Revenue generator module</td>
<td>5.8</td>
</tr>
<tr>
<td>CGM</td>
<td>Module</td>
<td>Cost generator module</td>
<td>5.9</td>
</tr>
<tr>
<td>FASM</td>
<td>Module</td>
<td>Fleet assignment module</td>
<td>4.2</td>
</tr>
<tr>
<td>TODGS</td>
<td>Subroutine</td>
<td>&quot;TrueO-D Generation&quot;</td>
<td>5.3</td>
</tr>
<tr>
<td>CAMS</td>
<td>Subroutine</td>
<td>&quot;Conservation_AircraftMovement&quot;</td>
<td>4.9</td>
</tr>
<tr>
<td>ARAS</td>
<td>Subroutine</td>
<td>&quot;AircraftRoutingAlgorithm&quot;</td>
<td>4.13</td>
</tr>
<tr>
<td>SCBS</td>
<td>Subroutine</td>
<td>&quot;SingleConnectionBuilder&quot;</td>
<td>4.22</td>
</tr>
<tr>
<td>DCBS</td>
<td>Subroutine</td>
<td>&quot;DoubleConnectionBuilder&quot;</td>
<td>4.23</td>
</tr>
<tr>
<td>PTGS</td>
<td>Subroutine</td>
<td>&quot;PassengerTypeGeneration&quot;</td>
<td>A.1</td>
</tr>
<tr>
<td>CTQS</td>
<td>Subroutine</td>
<td>&quot;ComputeTotalQSI&quot;</td>
<td>A.2</td>
</tr>
<tr>
<td>CFSWS</td>
<td>Subroutine</td>
<td>&quot;ComputeFlightServiceWeight&quot;</td>
<td>A.3</td>
</tr>
<tr>
<td>OPAPS</td>
<td>Subroutine</td>
<td>&quot;OnboardPaxAllocationProcess&quot;</td>
<td>A.4</td>
</tr>
<tr>
<td>ALCDS</td>
<td>Subroutine</td>
<td>&quot;AircraftLeaseCostDeterminant&quot;</td>
<td>5.10</td>
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<tr>
<td>LIOFS</td>
<td>Subroutine</td>
<td>&quot;LinkInboundOutboundFlights&quot;</td>
<td>4.14</td>
</tr>
<tr>
<td>ASGS</td>
<td>Subroutine</td>
<td>&quot;AircraftStringGeneration&quot;</td>
<td>4.15</td>
</tr>
</tbody>
</table>

Table 3.1: Summary of symbols that represent systems, modules, and subroutines

51
3.2 Basic Definitions Related to Airline Scheduling Systems

Before each module is explored in detail, there are some terms and concepts that need to be defined, as these terms will be used repeatedly throughout this dissertation.

□ Node

A node in terms of airline scheduling represents a point or station where a flight segment originates or terminates. Each node is associated with several attributes and some of these attributes are related to the geography of the node, such as a name, longitude and latitude of each airport. Other attributes are specifically related to each flight segment, such as departure time if it is an originating node, or arrival time if it is a terminating point of the flight segment. Still other attributes are related to a specific aircraft’s movement. If the node is used as a connecting point between inbound and outbound movements of aircraft, the node’s attributes will also include its ground and through times.

□ Leg (segment or link)

A leg is a flight segment that connects two airports (nodes) in the network system. This segment is nonstop, that is, flown by an aircraft without any en route stops between its initial take-off and final landing. A leg may also be called “segment” or “link.”

![Diagram of a leg/link/segment](image)

*Figure 3.3: Diagram of a leg/link/segment*
Chain (route)

A route or chain is a sequence of flight legs that connect two airports in an airline’s network system with one or more en route stops. As shown in Figure 3.4, two consecutive legs constitute a chain between Columbus (CMH) and Philadelphia (PHL) through Pittsburgh (PIT).

![Diagram of a chain or a route](image)

Figure 3.4: Diagram of a chain or a route

Airline network

An airline network is assumed to be sufficiently described by its segments (nonstop origin-destination pairs) and frequency of service. The airline network is basically composed of nodes and arcs (or routes/chains), and it can be constructed using an airline’s flight schedule. The airline network is represented as a two-dimensional space-time diagram, as shown in Figure 3.5.

![Airline network representation diagram](image)

Figure 3.5: Airline network representation diagram

\[ \Delta (\text{time zone}) = \text{difference in time zones between PST & EST} = 3 \text{ hours} \]

Each line indicates the directional flight leg flown by a particular aircraft.
Flight

A direct flight is a series of one or more flight segments specifically linked to provide through flight service to passengers in different markets. It may consist of only a single flight segment. A scheduled direct flight is the basic entity of interest; it consists of an itinerary, an aircraft type, and a set of event times. An itinerary is a sequence of two or more cities, where no city is repeated. The first city is the origin, the last city is the destination, and any intervening cities are known as en route or through cities. The entire flight designated, as a direct flight, has one flight number and is flown by the same aircraft.

A connecting flight itinerary is a sequence of two or more flight legs that form a path from one city to another and is assigned at least two different flight numbers. If a connection is made within a single airline network, then it is called an intraline connection. If a connection is made with more than one airline, then it is an interline connection. The last form of a connection is very similar to an interline connection in that more than one airline is involved; however, the connection is made among airlines that share a special marketing agreement intended to provide passengers with more convenient flight services. This special agreement, briefly discussed in Chapter 1, is called a strategic alliance, and the code-sharing agreement with a partner airline (or airlines) is the most important aspect of this agreement. A connection made with a partner airline is shown as an intraline connection because those airlines designate partner airlines’ flights as their own, using their own airline code and flight number in reservation systems. Figure 3.6 illustrates the relationships among different types of flight services, and Figure 3.7 shows some examples of these flight types.
Nonstop direct flight service in LAX-DFW market:

Figure 3.6: Different types of flight service

1-stop direct flight service in LAX-ORD market:

Intraline connecting flight services in LAX-LHR market:

Interline connecting flight service in NRT-CMH market:

* A number inside the parenthesis next to aircraft type indicates the tail number of an aircraft. Those flight segments that share an identical tail number indicate that the same aircraft will be flown those consecutive legs.

Figure 3.7: Examples of different types of flight service
Flight time & Block time

Block time is the elapsed time from the moment when parking blocks at a departure gate are removed from an aircraft to the moment when the blocks are replaced at the arrival gate. The flight segment block times between each consecutive pair of cities are generally different in each direction because of winds and the rotating direction of the earth. Flying time is the elapsed time between take-off and landing of an aircraft for a given segment. Figure 3.8 shows a typical mission profile of a commercial airliner to illustrate a difference between block time and flight time.

Source: Boeing document (November 1985)

Figure 3.8: A typical mission profile of a commercial airliner
Through time and Turnaround time (related to aircraft movement)

Both through time and turn-around time are associated with the movement of an individual aircraft at each station, not with each flight segment. As discussed in the “Flight” section, the intervening or en route-stop city for a direct flight is labeled as a through airport. At a through airport, some of the passengers of an aircraft do not get off the plane because their journey does not involve that en route-stop. Therefore, the time the aircraft has to stay on the ground is called the “through” time. When the plane reaches its final destination of a direct flight (it could be a nonstop, 1-stop, or 2-stop direct flight), all the passengers disembark the plane. Then, this aircraft can either stay at that airport overnight or be assigned to another flight segment. The time required for the plane to stay on the ground at this point is called the turnaround, or simply, the turn time.

In actual aircraft rotation practice, some of the turn time is associated with the terminating flight, in which case the plane stays overnight, while the remainder of the turn time is associated with the next assigned originating flight. Figure 3.9 illustrates the through time and turn time for a 2-stop direct flights.

Figure 3.9: Times associated with a 2-stop direct flight
Scheduling cycle

A scheduling cycle is the period of time in which the flight schedule is repeated. Usually, airline schedules are made either on a daily or on a weekly basis. A daily scheduled flight is a flight service offered seven days a week using the same flight number, departure and arrival times, and the same type of aircraft for the specified scheduling period. A weekly flight is a flight which operates only on certain days of the week. Most U.S. domestic flights are daily flights. Weekly scheduled flights are very common among international flights, since many international markets are not big enough to justify daily flight services.

Scheduling period

An airline schedule is planned for a given traffic season of the year and thus an airline may operate two, three or even four different schedules throughout a year. Each schedule, however, remains in effect for a period of several months, and this period is called a scheduling period. During each such scheduling period, the planning is performed on either a daily or a weekly basis, as appropriate.
CHAPTER 4

DEVELOPMENT OF FLIGHT SCHEDULE GENERATION SYSTEM

As stated earlier, it is difficult to develop computationally efficient integrated algorithms that deal with all the detailed aspects of airline scheduling, due to the large number of factors relevant to realistic airline schedule planning. Thus arises the need to combine consideration of a few factors common to the whole network (e.g. fleet sizes) with detailed constraints applicable to a particular route and a particular flight. Therefore, the entire airline scheduling problem can be distilled into two steps:

1) Each flight is scheduled in isolation to find the proper departure and arrival times and aircraft types to ensure that the detailed constraints applied to each route are satisfied;

2) After scheduling all flights for every route, the utilization of central resources are examined. If the proposed flight schedule is not feasible, step 1 is repeated for every flight which violates central resource constraints.

As shown in Figure 4.1, the flight schedule generation system is composed of three major sub-modules: a direct flight schedule generator module, an aircraft rotation module, and a connection builder module. A fleet assignment module is integrated into the direct flight schedule generator module.
Initial planning and decisions:
- Types of operation: Domestic vs. International
- Routes: city pairs
- Resources: types of available aircraft

Flight Schedule Generation System

For all the proposed city pairs:
Select next city pair

For all the proposed direct flight:
Select next direct flight

Inputs for direct flight segments:
- flight number, scheduling cycle, frequency, number of segments of a direct flight, and origin/destination airports

Fleet assignment module:
- assigns aircraft type to each flight

Is an assigned aircraft capable of flying the segment without violating any operating constraint?

1. direct flight is a sequence of flight segments that are flown using the same flight number and the same aircraft (same tail number)
2. a single leg for a nonstop flight, two consecutive legs for a 1-stop direct flight, and 3 consecutive legs for a 2-stop direct flight

Aircraft database

Figure 4.1: Flight schedule generation system
Store this flight data in a direct flight schedule file

End of direct flight list?

End of city pair list?

Aircraft rotation module:
⇒ generates aircraft routing plan & determines the minimum number of aircraft

Does a direct flight schedule provide a feasible aircraft routing?

Connection building module:
⇒ generates all possible connecting paths

Complete airline flight schedule timetable for a given scheduling period

(Figure 4.1: continued)
The output of this flight schedule generation system consists of a complete set of airline flight schedule timetables that list all flights, including nonstop flights, multi-stop direct flights (through flights), both intra-line and inter-line connections, and a complete aircraft rotation plan of all the aircraft used. The major inputs of this system are the type of available fleet of an airline, the list of city pairs an airline wants to offer service to, and the list of preferred local departure and arrival times. The flight schedule generation system also requires several databases of essential information. One of the necessary databases is an airport database that contains not only geographic information of major airports around the world but also any operational constraints of each airport, such as the time period of curfew at an airport. Also required is an aircraft database that specifies all the operating performance characteristics of different aircraft types.

4.1 Direct Flight Schedule Generation System

This system is used to generate all the nonstop flight legs that represent direct flight services for the city pairs in an airline’s network system. Figure 4.2 illustrates detailed steps implemented in the direct flight schedule generator module. This module takes the variables determined in the initial planning and decision stage as shown in Figure 4.1. During the stage illustrated in Figure 4.1, some of the fundamental strategic decisions have to be made in terms of an airline’s type of operation and basic network structures.
Start direct flight schedule generator module

For all the city pairs

For all the direct flight segments

Inputs for direct flight segments:
- flight number, scheduling cycle,
  frequency, number of segments of a
direct flight, and
origin/destination airports

Fleet assignment module:
- assigns aircraft type to each flight

Retrieved aircraft data:
- speed, range, cabin configuration, etc.

1. Set No_Stop as # of en route-stops for a selected direct flight
2. Set No_Link as # of segments that constitutes
   a single direct flight  \( \Rightarrow \) No_Link = No_Stop + 1

For I = 1 to No_Link

Compute great circle distance of link, \( I \Rightarrow GCD(i) \)

Is an assigned aircraft
capable of flying the segment ?
\( \Rightarrow A/C \text{ Range } \geq GCD(i)+\varepsilon ? \)

1. Maximum number of links that
   can constitute a single direct flight
   (path that is composed of links) is 3.

2. \( \varepsilon \) is an extra distance an aircraft
   should be able to fly in case of
   emergency

Figure 4.2: Direct flight schedule generator module
Set departure time at an originating airport of a selected direct flight:
Case 1: first segment of a direct flight or a nonstop direct flight
\[ \text{Dep}_\text{Time}(i) = \text{predetermined departure time (given as an input)} \]
Case 2: subsequent segment of a direct flight (2nd or 3rd segment)
\[ \text{Dep}_\text{Time}(i) = \text{Arr}_\text{Time}(i-1) + \text{Through}_\text{Time}^3 \]

1. Compute flying time for this flight segment
\[ \text{Flying}_\text{Time}(i) = \text{GDC}(i) \div \text{(Aircraft speed)} \]
2. Compute block time for this flight segment
\[ \text{Block}_\text{Time}(i) = \text{Flying}_\text{Time}(i) + \text{Taxi-in/out}_\text{Time} + \text{e} \]

Compute arrival time at an arriving airport of a flight segment, \( i \):
\[ \text{Arr}_\text{Time}(i) = \text{Dep}_\text{Time}(i) + \text{Block}_\text{Time}(i) \]

Does the arrival time violate any operating restriction such as a curfew?

Last segment of this direct flight?

Yes

Store this flight data in a direct flight schedule file

End of direct flight list?

Yes

No

End of city pair list?

Yes

No

Return

* Dep.Time(i) = departure time of a direct flight segment, i:
  * Arr.Time(i-1) = arrival time of the previous flight segment of the same direct flight for a one-stop, 2-stop, or 3-stop direct flight;
  * Through.Time(i) is the time required for an aircraft to be serviced and for passengers to disembark and board a plane at an en route-stop (connecting node between inbound and outbound flights)

(Figure 4.2: continued)
One of important decisions that has to be made in the initial planning stage of an airline’s basic network system is whether an airline’s route network system will be limited to only domestic markets or expanded to international markets. Once that decision is made, all the city pairs where an airline plans to provide flight services, type of each flight itinerary in each market, and the frequency of proposed flights must be determined. All these decision variable are input data for the direct flight schedule generator module. Once this input is prepared, the direct flight schedule generator module can be initiated to generate all flight segments.

For each nonstop direct flight segment, there are some attributes associated with its nodes and links. A simple network diagram shown in Figure 4.3 is used to illustrate the attributes associated with nodes (airports), segments (flight legs), and chains (flight itineraries).

![Figure 4.3: A simple network diagram](image)

<table>
<thead>
<tr>
<th>Node index</th>
<th>Node</th>
<th>Node name</th>
<th>Longitude</th>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>ORD</td>
<td>87.54W</td>
<td>41.58N</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>CMH</td>
<td>82.52W</td>
<td>39.59N</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>ATL</td>
<td>84.26W</td>
<td>33.39N</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>EWR</td>
<td>74.10W</td>
<td>40.41N</td>
</tr>
</tbody>
</table>

*Table 4.1: Attributes associated with nodes*
Table 4.1 shows all the attributes associated with each node. The attributes of a node are mostly related to its geography. Table 4.2 lists the attributes associated with each link. Some of these attributes are related to the aircraft assigned to each segment. The attributes associated with chains or flight itineraries are listed in Table 4.3.

<table>
<thead>
<tr>
<th>Link #</th>
<th>Link ID</th>
<th>Node of Dep</th>
<th>Node of Arr</th>
<th>Aircraft</th>
<th>Seats</th>
<th>Time of Dep</th>
<th>Time of Arr</th>
<th>GCD</th>
<th>B.H.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flt1_1M</td>
<td>A</td>
<td>B</td>
<td>AC(1)</td>
<td>S(1)</td>
<td>TD(1)</td>
<td>TA(1)</td>
<td>GCD(1)</td>
<td>BH(1)</td>
</tr>
<tr>
<td>2</td>
<td>Flt1_2M</td>
<td>B</td>
<td>C</td>
<td>AC(2)</td>
<td>S(2)</td>
<td>TD(2)</td>
<td>TA(2)</td>
<td>GCD(2)</td>
<td>BH(2)</td>
</tr>
<tr>
<td>3</td>
<td>Flt2_0M</td>
<td>B</td>
<td>D</td>
<td>AC(3)</td>
<td>S(3)</td>
<td>TD(3)</td>
<td>TA(3)</td>
<td>GCD(3)</td>
<td>BH(3)</td>
</tr>
<tr>
<td>4</td>
<td>Flt3_0M</td>
<td>A</td>
<td>D</td>
<td>AC(4)</td>
<td>S(4)</td>
<td>TD(4)</td>
<td>TA(4)</td>
<td>GCD(4)</td>
<td>BH(4)</td>
</tr>
</tbody>
</table>

Table 4.2: Attributes associated with links

Notes on Table 4.2:
1. Link ID is an identification code that includes an airline code, a flight number, and a section number if this segment is a part of a multi-stop flight itinerary. For example, Flt1_1M indicates that this flight segment is the first section of a multi-stop flight, Flt1 that operates on Monday. A “0” in Flt2_0M indicates that this is a nonstop direct flight.
2. Departure.
3. Arrival. Arrival times of each node in the network system are computed by the system.
4. Great circle distance between two airports.
5. Block hour of the selected link between two nodes.

<table>
<thead>
<tr>
<th>Chain</th>
<th>Flight type</th>
<th>Transit time</th>
<th>Sequence of nodes</th>
<th>Sequence of links</th>
<th>Total GCD</th>
<th>Total trip time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chain(1)</td>
<td>Dir_0</td>
<td>TT(1)</td>
<td>A B</td>
<td>Flt1_1M</td>
<td>TGCD(1)</td>
<td>TTIME(1)</td>
</tr>
<tr>
<td>Chain(2)</td>
<td>Dir_1</td>
<td>TT(2)</td>
<td>A C</td>
<td>Flt3_0M</td>
<td>TGCD(2)</td>
<td>TTIME(2)</td>
</tr>
<tr>
<td>Chain(3)</td>
<td>Dir_1</td>
<td>TT(3)</td>
<td>A B C</td>
<td>Flt1_1M Flt1_2M</td>
<td>TGCD(3)</td>
<td>TTIME(3)</td>
</tr>
<tr>
<td>Chain(4)</td>
<td>Cnx_1</td>
<td>TT(4)</td>
<td>A B D</td>
<td>Flt1_1M Flt2_0M</td>
<td>TGCD(4)</td>
<td>TTIME(4)</td>
</tr>
<tr>
<td>Chain(5)</td>
<td>Dir_0</td>
<td>TT(5)</td>
<td>B C</td>
<td>Flt1_2M</td>
<td>TGCD(5)</td>
<td>TTIME(5)</td>
</tr>
<tr>
<td>Chain(6)</td>
<td>Dir_0</td>
<td>TT(6)</td>
<td>B D</td>
<td>Flt2_0M</td>
<td>TGCD(6)</td>
<td>TTIME(6)</td>
</tr>
</tbody>
</table>

Table 4.3: Attributes associated with chains
Notes on Table 4.3:

1. The type of flight itinerary in a market between the first node and the last node listed in the sequence of nodes column. A nonstop direct flight itinerary is indicated as Dir_0 and any other direct flight itinerary includes a number of stops (i.e., Dir_2 for a 1-stop direct flight service, etc.). A connecting flight service is represented by "Cnx" with a number indicating number of stops. Cnx_1 indicates a connecting flight service with one stop.

2. Transit time at each en route stop node. It represents either a connecting time or a through time depending on the type of stop. If it is a direct flight service, then this transit time refers to a through time (i.e., TT(2)). However, if a stop is required as part of connecting flight itinerary, the transit time refers to a connecting time (i.e., TT(4)). Since there is no transit time required for a nonstop flight, TT(1), TT(5), and TT(6), is zero.

3. The first and last nodes in the sequence of nodes designates origin and destination market (O&D or O-D), defined by a passenger's point of entry and exit from the airline system. Other nodes indicate either a through stop or a connecting point.

4. TGCD stands for a total great circle distance, which is the total distance of an entire flight itinerary (chain).

\[ TGCD(i) = \sum_{l=1}^{L}(GCD(l)) \quad \text{where } GCD(l) \text{ is a great circle distance of a link, } l \]

5. TTIME is the total trip time to travel from an origin airport to a destination airport in a particular flight chain.

\[ TTIME(i) = \sum_{l=1}^{L} BH(l) + \sum_{n=1}^{N} TT(n) \quad \text{where } BH(l) \text{ is a block hour of a link, } l \text{ and } TT(n) \text{ is a transit time of a node, } n \]

For any through flight itinerary that serves a true O&D market, the maximum number of allowed flight legs is limited to three. In today's highly connected airline network system, especially within the Continental United States, the likelihood of traveling from one city to another with more than two en route stops is extremely small. The same is true for connecting flight itineraries.

Once all the input data, such as a designated flight number, flight frequency, origin and destination airport, and departure time of the segment, are entered, the system assigns a predetermined aircraft type to the flight segment and determines the arrival time.
at the destination airport. When assigning an aircraft type, the system automatically checks whether the assigned aircraft is capable of flying the segment. For an assigned aircraft to be able to fly the segment, the range of the assigned aircraft should be greater than or equal to the sum of a great circle distance of the link plus the distance designated as a reserve in Figure 3.8 (Mission profile of a commercial airliner):

Computing Great Circle Distances

The purpose of computing direct-line distance is quite complex. The method of computing the great circle distance, however, is much simpler, as shown in the formula and example below. The two methods yield slightly different results, but the difference is negligible enough that we can use the formula for great circle distance as a more efficient means of arriving at the direct-line distance [99].

\[
\text{Distance} = \{ \cos^{-1} \left[ \sin(L_1) \times \sin(L_2) + \cos(L_1) \times \cos(L_2) \times \cos(DL_0) \right] \} \times \Phi
\]

where

- \( L_1 \) = the latitude of airport 1 in degrees
- \( L_2 \) = the latitude of airport 2 in degrees
- \( DL_0 \) = the difference in longitude between airports 1 and 2 in degrees
- \( \Phi = \theta \times \text{radius of earth} = 1^\circ \times 3959.14161298 \text{ miles} = 69.16 \text{ miles} \)

* Converting minute and second into degrees:

\( X^\circ Y' Z'' = (X + (Y/60) + (Z/3600)) \text{ degrees} \)

* Sign convention of latitude and longitude

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern (N)</td>
<td>Southern (S)</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>
Numerical Example:

Airports Coordination

<table>
<thead>
<tr>
<th></th>
<th>Coordination</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHL</td>
<td>Latitude: 39° 52' 1&quot; N = (39 + \frac{52}{60} + \frac{1}{3600})° = + 39.8669° = L_1</td>
</tr>
<tr>
<td></td>
<td>Longitude: 75° 14' 9&quot; W = -75.2358°</td>
</tr>
<tr>
<td>ORD</td>
<td>Latitude: 41° 58' 7&quot; N = +41.9686° = L_2</td>
</tr>
<tr>
<td></td>
<td>Longitude: 87° 54' 4&quot; W = -87.9011°</td>
</tr>
</tbody>
</table>

DL₀ = \(-75.2358 - (-87.9011)\) = 12.6653

\[ \text{Distance} = \left\{ \cos^{-1}\left[ \sin(39.8669) \times \sin(41.9686) + \cos(39.8669) \times \cos(41.9686) \times \cos(12.6653) \right] \right\} \times 69.16 \]

\[ = 676.986 \text{ miles} \rightarrow \text{Great circle distance} \]

* Actual distance listed in Official Airline Guide (OAG) = 663 miles

\[ \therefore \% \text{ difference between great circle distance and direct-line distance (air distance)} \]

\[ = \frac{676.986 - 663}{676.986} \times 100 = 2.07\% \]

\[ \therefore \text{It is safe to assume that the method to compute great circle distance is accurate enough to be used to compute the air distance between two airports.} \]

Determining discrepancy in block hours between two airports depending on the direction of a flight segment

As illustrated in Figure 4.4, the equation to determine a block hour of a link includes a term, ε, that represents the extra time that should be added to a flight segment whose flying direction is the opposite of the rotating direction of the earth. Figure 4.5 illustrates the logic and algorithm used in determining whether the value of ε should be added to the equation that computes block hours. Figure 4.6, then, presents a graphical
representation of the relationships between the directions of flight segments and the
differences in longitudes of each flight's origin and destination.

\[
\begin{align*}
\text{Compute Block\_Time} \\
\Delta(\text{Lon}) &= \text{Longitude of Destination} - \text{Longitude of Origin} \\
\text{GCD\_Leg} &= \text{great circle distance of a flight leg} \\
\text{GCD\_Leg} &\leq 300 \text{ mi.} \\
\text{Abs}(\Delta(\text{Lon})) &> 180 \\
\text{Abs}(\Delta(\text{Lon})) &\leq 180 \\
\text{Abs}(\Delta(\text{Lon})) &\geq 355 \\
\text{Abs}(\Delta(\text{Lon})) &< 0 \\
\text{Abs}(\Delta(\text{Lon})) &> 0 \\
\varepsilon &= 0 \\
\varepsilon &= 0.2925 \times \text{Abs}(\Delta(\text{Lon})) \\
\text{Block\_Time} &= \text{Flying\_Time} + \text{Taxi\_in/out\_Time} + \varepsilon \\
\text{Return Block\_Time}
\end{align*}
\]

Notes:
1. Determines the proximity of the origin and destination of the flight segment.
2. Determines if two nodes that constitutes a selected flight segment are located in the same hemisphere (east or west).
3. Determines if two nodes that constitutes a selected flight segment are located closer longitudinally.
4. Determines the direction of the flight segment with respect to the rotating direction of the earth.

Figure 4.4: Logic of determining block hours

70
To normalize the value of $\varepsilon$ and find the relationship between the value of $\varepsilon$ and the longitudinal distance from the origin airport to the destination airport, actual differences in block hours of flight segments of both directions versus differences in longitude between the flight segment's origin and destination were recorded, and a linear
regression was performed. Figure 4.6 shows the equation obtained from the linear regression. This equation is implemented in the system to determine values of ε of some of the flight segments.

\[ e = 0.2925 \times (\delta(\text{Lon})) + 19.353 \]

Source: SABRE's Travelocity and Microsoft Expedia websites

Figure 4.6: Difference in block hours between the flight segments flying in opposite directions of the same two airports versus differences in longitudes of the two airports

4.2 Fleet Assignment Routine

The fleet assignment problem is concerned with the assignment of aircraft types to each flight segment in a given schedule, such that total network profitability is optimized, while a basic set of constraints is satisfied. The main objective of the fleet assignment problem for this system is to assign proper aircraft types to flight segments to achieve better load factors without violating any operational constraints.

4.3 Aircraft Routing Module

Within the framework of the airline scheduling system, planning aircraft rotations poses numerous challenges to an airline. Once fleet types have been assigned to a set of flight segments (not specific planes) as in the previous module, the actual assignment of specific aircraft, or tail numbers, to the flight schedule must be performed. This will
generate a routing plan of each aircraft during a given scheduling cycle (in this case, on a weekly basis) and determine the feasible number of aircraft needed to satisfy the developed flight schedule. This stage of the process yields the aircraft rotation plan. Figure 4.7 shows the overall flow of this aircraft routing module.

Figure 4.7: Aircraft routing module
4.3.1 Conservation of Aircraft Movement

One of the most important requirements in an airline’s aircraft routing system is the avoidance of deadheadings of aircraft at certain airports during a given scheduling cycle (weekly scheduling cycle). Thus, an algorithm which produces an aircraft rotation plan that reduces deadheadings is essential. Even though most domestic flights are operated on a daily basis, a majority of international and some domestic flights operate only on certain days of the week. Therefore, the algorithm of the system is designed to generate a weekly aircraft routing plan instead of a simple daily routing plan. To ensure that an aircraft is present at the proper airport and on time for each departure, the number of aircraft arriving at a given station is to be equal to the number aircraft departing from the same station for a given scheduling period. Further, the balance must be reached within the same aircraft type’s arrival and departure pairs.

![Balanced aircraft movement](image1)

![Unbalanced aircraft movement](image2)

*Figure 4.8: Examples of balanced and unbalanced aircraft movement*
Check conservation of aircraft movement subroutine

For \( i = 1 \) to No_Station

\( \star \) Station(i)

For \( j = 1 \) to No_AircraftType

\( \star \) ACType(j)

**Initialization:**

Set Count_Inbound = 0; Count_Outbound = 0

Read each flight segment record in a "direct flight schedule file":

For \( k = 1 \) to EOF: \( \star \) Flight_Link(k)

Aircraft of Flight_Link(k) = ACType(j) ?

Yes

No

(Station(i)=Origin of Flight_Link(k)) Or (Station(i)=Destination of Flight_Link(k)) ?

Yes

No

If (Station(i)=Destination of Flight_Link(k))

\( \star \) Count_Inbound = Count_Inbound + 1

If (Station(i)=Origin of Flight_Link(k))

\( \star \) Count_Outbound = Count_Outbound + 1

End of direct flight segments file?

Yes

No

(Count_Inbound = Count_Outbound) ?

Yes

No

End of A/C list?

Yes

No

End of station list?

Yes

Return

Figure 4.9: Conservation of aircraft movement algorithm
Figure 4.8 illustrates the difference between the balanced and unbalanced aircraft movement at any given node. This process, shown in Figure 4.9 in great detail, is referred to as a conservation of aircraft movement. A mathematical representation of conservation of aircraft movement that balances inbound and outbound aircraft activities of the same aircraft type is shown as follows:

\[
\sum_{n=1}^{N} \sum_{i=1}^{I} \sum_{k=1}^{K} (\text{Inbound flight})_{nk} = \sum_{n=1}^{N} \sum_{i=1}^{I} \sum_{m=1}^{M} (\text{Outbound flight})_{nm}
\]

where  
- \( N \) = a total number of nodes (station) in the network system;
- \( I \) = a total number of aircraft type (not individual aircraft);
- \( K \) = a total number of inbound flights of aircraft type, \( i \), at a station, \( n \);
- \( M \) = a total number of outbound flights of aircraft type, \( i \), at a station, \( n \);

4.3.2 Determination of a Feasible Number of Aircraft and Construction of Aircraft Routing Plans

Once a complete direct flight schedule is generated, all flight segments can be represented in a space-diagram. The space-diagram, as shown in Figure 4.10, is composed of multiple lines that represent a weekly scheduling cycle. Each line is devoted to a particular airport in an airline's network system. Nodes at each line indicate either inbound movements (arrivals) or outbound movements (departures), depending on the direction of the line that is connected to each node. This directed line that connects between time lines of two airports represent a particular direct flight segment. Times shown in the time lines are all local times, which reflect time zone changes among different regions around the world.
As a next step, this space-time diagram should be converted to a network diagram (Figure 4.11) in which nodes represent scheduled flight segments. In this network diagram, a branch is directed from node \( x_i \) towards node \( x_j \) only if the same aircraft can be assigned to flight \( x_j \) after flight \( x_i \).

\[ \text{Figure 4.10: Space-time diagram} \]

\[ \text{Figure 4.11: Network diagram in which nodes represent flights} \]
This diagram then is used to construct a bipartite graph which must be constructed for each airport in an airline’s network system. A bipartite graph of a particular airport is composed of two lines that include nodes of a sink and a target, as shown in Figure 4.12. A sink node indicates an inbound flight segment and a target node indicates an outbound flight segment. A branch is directed from \( S_i \) towards node \( T_j \) only if the same aircraft can be assigned to flight \( S_j \) after flight \( t_i \).

```
Figure 4.12 Bipartite graph
```

Figure 4.13 show an overall process of determining a feasible number of aircraft by each aircraft type and generating each individual aircraft’s weekly rotating plan. Then, Figures 4.14, and 4.15 show the flowcharts of subroutines implemented within the aircraft routing algorithms. The methods that are illustrated in these three flowcharts and in a case study shown in the Section, 4.3.3, show in detail how the bipartite graph representations can be used to determine the feasible number of aircraft needed to serve a given flight schedule and to generate a complete aircraft rotation plan.
Aircraft routing algorithm subroutine

For I=1 to No_AircraftType
  & ACType(i)

For J=1 to No_Station
  & Station(j)

Read each flight segment record in a "direct flight schedule file":
  For K=1 to EOF:
    & Flight_Link(k)

  Aircraft of Flight_Link(k) = ACType(i) ?

     Yes

     (Station(i)=Origin of Flight_Link(k)) Or
     (Station(i)=Destination of Flight_Link(k))

     Yes

     If (Station(i)=Origin of Flight_Link(k))
       & Store data of Flight_Link(k) as outbound
       flight link at Station(i) in a file, OusboundFile

     If (Station(i)=Destination of Flight_Link(k))
       & Store data of Flight_Link(k) as inbound
       flight link at Station(i) in a file, InboundFile

     No

End of direct flight segments file?

Yes

A

No

Figure 4.13: Aircraft routing algorithm
Sort *InboundFile* and *OutboundFile* by direct flight segments' arrival times and departure times, respectively.

**"LinkInboundOutboundFlights" subroutine:**
Link inbound and outbound flight segments at stations based on predetermined criteria (e.g., flight #14 — flight #56)

Store all the linked chain of flight segments in one of 2 bipartite files (*BipartiteFile* & *BipartiteFile1*).

End of station list? Yes

**"AircraftStringGeneration" subroutine:**
- This subroutine determines the feasible number of aircraft needed for a developed flight schedule and generates weekly aircraft routing schedules for all aircraft.

End of A/C list? Yes

Return

(Figure 4.13: continued)
Read each flight segment record in OutboundFile:
For I=1 to EOF: Flight_Oub(I)

Read each flight segment record in InboundFile:
For J=1 to EOF: Flight_Inb(J)

Link direct flights:
( Flight # of Flight_Link(k)
= flight # of Flight_Link(k) ) ?

Store a linked chain of flight segments in a bipartite file & remove these flight segments from both InboundFile & OutboundFile

Link flight segments based on pre-set A/C turn time:
TurnTime_Minimum < (Departure time of Flight_Oub(I)
- arrival time of Flight_Inb(J) ) < TurnTime_Maximum ?

Figure 4.14: Algorithm to illustrate how to link inbound and outbound aircraft movements
Store a linked chain of flight segments in BipartiteFile and remove these flight segments from both InboundFile & OutboundFile.

- End of InboundFile?
  - Yes: Return
  - No: Read each flight segment record in InboundFile:
    - For J=1 to EOF: Flight_Inb(j)
    - Store an unlinked flight segment left in InboundFile as a terminating flight of a flight string for a selected aircraft in BipartiteFile & remove this flight segment from InboundFile
    - End of InboundFile?
      - Yes: Return
      - No: Read each flight segment record in OutboundFile:
        - For I=1 to EOF: Flight_Oub(i)
        - Store an unlinked flight segment left in OutboundFile as an originating flight of a flight string for a selected aircraft in BipartiteFile & remove this flight segment from OutboundFile
        - End of OutboundFile?
          - Yes: Return
          - No: End of OutboundFile?

1. BipartiteFile contains both inbound and outbound flight segments (Link_Inb & Link_Oub) that are linked as a chain of aircraft movement at a specified station. Each flight segment is represented by its FlightSegmentId which represents the flight identification of a particular flight segment, and it contains such information as the segment number of a direct flight and a day of the week which it operates. This identification is required since the system is considering a weekly scheduling cycle.

(Figure 4.14: continued)
"AircraftStringGeneration" subroutine

Read each originating flight segment record in BipartiteFile1:
For K=1 to EOF: ♦Link_Start(k)

Initializations:
① to generate a string of airports for this aircraft:
   Set S = 1
② to generate a string of flight segments for this aircraft:
   Set F = 1
③ to compute a total flying distance & block hours of each aircraft:
   Set Total_Dist= 0; Total_BlkHrs = 0

Retrieved data of Link_Start(k):
   Link_Start_Id = flight segment identification of Link_Start( k)
   Link_Start_Org = origin airport of Link_Start( k)
   Link_Start_Dest = destination airport of Link_Start( k)
   Link_Start_Dist = flying distance of Link_Start( k)
   Link_Start_BlkIr = block hour of Link_Start( k)

* Compute & update total distance and block hours of this aircraft:
  Total_Dist= Total_Dist + Link_Start_Dist
  Total_BlkHrs = Total_BlkHrs + Link_Start_BlkHr

* Update a string of flight segments for this aircraft for a given scheduling cycle:
  Flight_String(f) = Link_Start_Id

* Update a string of airports for this aircraft for a given scheduling cycle:
  Station_String(s) = Link_Start_Org
  Station_String(s+l) = Link_Start_Dest

Figure 4.15: Aircraft string generation subroutine
Read each inbound & outbound flight segment that is linked as a chain in BipartiteFile:
For M=1 to EOF: *Link_Inb(m) & Link_Oub(m)

Retrieved data of Link_Inb(m):
Link_Inb_Id = flight segment identification of Link_Inb(m)
Link_Inb_Org = origin airport of Link_Inb(m)
Link_Inb_Dest = destination airport of Link_Inb(m)
Link_Inb_Dist = flying distance of Link_Inb(m)
Link_Inb_BlkHr = block hour of Link_Inb(m)

Retrieved data of Link_Oub(m):
Link_Oub_Id = flight segment identification of Link_Oub(m)
Link_Oub_Org = origin airport of Link_Oub(m)
Link_Oub_Dest = destination airport of Link_Oub(m)
Link_Oub_Dist = flying distance of Link_Oub(m)
Link_Oub_BlkHr = block hour of Link_Oub(m)

(Link_Start_Id = Link_Inb_Id) ?
Yes

* Compute & update total distance and block hours of this aircraft:
Total_Dist= Total_Dist + Link_Oub_Dist
Total_BlkHrs = Total_BlkHrs + Link_Oub_BlkHr

* Update a string of flight segments for this aircraft for a given scheduling cycle:
f=f+1
Flight_String(f) = Link_Oub_Id

* Update a string of airports for this aircraft for a given scheduling cycle:
s=s+1
Station_String(s) = Link_Oub_Dest

(Figure 4.15: continued)
Read each inbound & outbound flight segment that is linked as a chain in BipartiteFile:
For N=1 to EOF: \( \bullet \) Link_Inb\( (n) \) & Link_Oub\( (n) \)

Retrieve data of Link_Inb\( (n) \) & Link_Oub\( (m) \):
\( \bullet \) Assign the same variables as in the previous iteration
(Data block 1)

\( \text{No} \)

\( \text{Yes} \)

Is Link_Inb\( (n) \) a terminating flight?
\( \text{No} \)

\( \text{Yes} \)

* Compute & update total distance and block hours of this aircraft:
\( \text{Total_Dist} = \text{Total_Dist} + \text{Link_Oub_Dist} \)
\( \text{Total_BlkHrs} = \text{Total_BlkHrs} + \text{Link_Oub_BlkHr} \)

* Update a string of flight segments for this aircraft for a given scheduling cycle:
\( f = f + 1 \); FlightId\( (f) = \text{Link_Oub_Id} \)

* Update a string of airports for this aircraft for a given scheduling cycle:
\( s = s + 1 \); Station\( (s) = \text{Link_Oub_Org} \)

\( \text{N=1 (inner loop): Start scanning from the first record} \)
\( \text{No} \)

\( \text{Yes} \)

End of BipartiteFile (outer loop)?
\( \text{No} \)

\( \text{Yes} \)

Store a complete string of an aircraft in a file

End of BipartiteFile? \( \text{No} \)

\( \text{Yes} \)

Return

(Figure 4.15: continued)
4.3.3 Case examples of aircraft routing problem

Figure 4.16 shows a simple airline network system that represents a direct flight segment flown by the same type of aircraft (e.g., B757-200) for a given scheduling cycle. Even though the actual computer system can handle a complicated weekly cycle, this example assumes a daily scheduling cycle. In the actual computer system, the network system shown in Figure 4.16 is generated in the direct flight schedule generator module. However, the direct flight schedule generator module only assigns an aircraft type to each flight segment without generating a weekly rotation plan of each aircraft. Then, the aircraft rotation module determines the feasible number of aircraft by each aircraft type and generates a weekly aircraft rotation plan of each individual aircraft.

* Simple network structure of a particular aircraft type (e.g., B757-200) for a given scheduling cycle (a week)
* All the flight segments shown in this network must be flown by the same aircraft type, but not necessarily by a single aircraft. The system using developed algorithms will determine the minimum number of aircraft of this particular aircraft type (e.g., B757-200) and generate a weekly aircraft rotation plan of each aircraft. Since the solution for this network system only applies to one aircraft type, the same process should be performed for all the aircraft types in airline's fleet.

![Sample network diagram](image-url)

*Figure 4.16: Sample network diagram*
Solution step 1: Constructing an initial bipartite graph

* Shaded source node indicates a terminating flight segment of a chain of a particular aircraft's rotation for a given scheduling cycle. The aircraft assigned to this terminating flight segment is then available for an originating flight segment at the same station for the next scheduling cycle.

Figure 4.17: Initial bipartite graph

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Solution step 2: Constructing a final bipartite graph

Figure 4.18: Final bipartite graph
Aircraft routing solution

*Same Aircraft Type (e.g., B757-200)*

Aircraft #1: ORD → CMH → CA301 → STL

Aircraft #2: BOS → CA501 → CMH → CA800 → ATL

Aircraft #3: STL → CA300 → CMH → CA201 → DEN → CA334 → LAS

Aircraft #4: MCO → CA223 → PHL → CA223 → EWR → CA601 → CMH → CA500 → BOS

Aircraft #5: DFW → CA400 → CMH → CA401 → DFW

Aircraft #6: LAS → CA333 → DEN → CA200 → CMH

Aircraft #7: MCO → CA445 → PHL → CA701 → CMH

Aircraft #8: CMH → CA101 → ORD

Aircraft #9: CMH → CA600 → EWR → CA222 → PHL → CA222 → MCO

Aircraft #10: DFW → CA111 → STL → CA112 → DFW

Aircraft #11: ATL → CA801 → CMH → CA700 → PHL → CA444 → MCO

**Figure 4.19: Aircraft rotation plan**

Arcs connecting source and target nodes shown in Figures 4.17 indicate that an aircraft assigned to the flight number of the source node can be available to those flight numbers of the target nodes. Next, Figure 4.19 shows a final solution that shows an aircraft movement chain at each station. A modified FIFO (first-in-first-out) method is applied to solve the problem.
Conservation of Aircraft movement check

This process is needed to ensure that the network system shown in Figure 4.16 provides operationally feasible aircraft rotation plans that reduces the amount of deadheading of aircraft at certain stations for a given scheduling period.

### Table 4.4: Conservation of aircraft movement

<table>
<thead>
<tr>
<th>Station (Node)</th>
<th># of inbound flights</th>
<th># of outbound flights</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAS</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>DEN</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>STL</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DFW</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>ORD</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CMH</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>ATL</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>BOS</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>EWR</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>PHL</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>MCO</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

1. # of flights flown by the same type of aircraft

### Table 4.5: Balancing the number of aircraft

<table>
<thead>
<tr>
<th>Station</th>
<th># of aircraft at the beginning of cycle</th>
<th># of aircraft at the end of cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORD</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>BOS</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>STL</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MCO</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DFW</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>LAS</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>ATL</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CMH</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Solution: balanced number of aircraft at the beginning and the end of the scheduling cycle

Table 4.5: Balancing the number of aircraft
4.4 Connection Builder Module

One of the most important aspects of an airline’s hub-and-spoke network system is that the system can provide numerous connecting flight itineraries to markets that are not big enough to justify either nonstop or through direct flights. By providing the right mix of connecting flight services, an airline can generate additional revenues on the existing flight segments in addition to the revenues generated by each flight segment’s local traffic. Incidentally, in today’s highly connected route network of complicated hub-and-spoke systems, about fifty-five percent of total passenger revenues is generated by those connecting passengers[82]. Clearly, as the network is altered in terms of nonstop flight segment coverage or frequency, the connecting opportunities are also changed partly because of discrepancies in operating days of flights that can form a flight itinerary to a certain market. Therefore, an important component of route planning models is a connection builder that can rapidly respond to modified network of direct flight segments.

To better understand how each of these connections are made at a hub airport, some of the terms that are associated with operating connecting services must be discussed. The terms “complex,” and “bank,” (or wave) are used to describe groups of aircraft at a hub that arrive or depart within a window of time allowing passengers to make connections. A complex is a group of inbound aircraft arriving at a hub airport during a specified arrival window or a group of outbound aircraft departing from the hub airport during a specified departure window. Figure 4.20 shows a graphical representation of the relationships among these terms. Table 4.6 shows that the number
of markets served through a hub utilizing these complex and bank combinations grows exponentially as aircraft are added in the complex.

**Figure 4.20: Graphical representation of a connecting complex and a bank**

<table>
<thead>
<tr>
<th># of aircraft in a bank</th>
<th># of markets served</th>
<th>Local market</th>
<th>Connecting market</th>
<th>Total # of markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>9</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>25</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>100</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>40</td>
<td>400</td>
<td>440</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>80</td>
<td>1,600</td>
<td>1,680</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>100</td>
<td>2,500</td>
<td>2,600</td>
<td></td>
</tr>
</tbody>
</table>

1. A number of inbound flights which must be equal to a number of outbound flights of a specified connecting bank
2. # of markets = A(2+A) where A is the number of aircraft listed in the first column

*Table 4.6: Potential number of markets that can be served by connections*
A flow chart in Figure 4.21 illustrates an overall structure of the connection builder module.

Start Connection Building Module

Scan "direct flight schedule file" to create files that list all airports in an airline's network

"SingleConnectionBuilder" routine

"DoubleConnectionBuilder" routine

End connection building module

*Figure 4.21: Connection builder module*

The first step in the process of building connecting paths is to perform a search through the direct flight schedules to find all possible paths that can transport passengers from one city to another by flying more than one flight segment. In addition, a systematic search is performed for all reasonable connecting paths. The module automatically creates and deletes connecting paths based on predetermined criteria, such as a distance and time circuitry rule (based on nonstop great circle distance and flying time), and the minimum and maximum connecting times by airport types and connection types (intraline or interline and domestic or international). However, the system is also designed to overrule all the specified criteria to create connecting paths manually. One important constraint on this module is the number of links that can be connected to create possible connecting paths. The two most common connection types in terms of the
number of links are single connections which are linked with two different flight numbers and double connections which consist of three different flight numbers. In today's highly competitive airline industry, where most airlines are utilizing hub-and-spoke systems and many strategic alliances are formed globally, it is rare for a passenger to travel from one point to another by connecting more than three links (double connections). Therefore, it was determined that the system would only take into consideration single and double connections. Flowcharts shown in Figures 4.22 and 4.23 illustrate detailed algorithms implemented for building single connections and double connections, respectively, based on the nonstop flight segments network.

![Flowchart for SingleConnectionBuilder Subroutine](image)

**Figure 4.22: Single connection builder**

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Read each flight segment record in a sorted InboundFile:
For K=1 to EOF: *Flight_Inb(k)

Read each flight segment record in a sorted OutboundFile:
For M=1 to EOF: *Flight_Oub(m)

Connect direct flights:
( Flight # of Flight_Inb(k) = flight # of Flight_Oub(m) )?

Store the linked direct flight segments in a single connection file as an one-stop direct flight

Connect flight segments based on pre-set minimum & maximum connecting times:
CnxTime_Min < (Departure time of Flight_Oub(m) - arrival time of Flight_Inb(k)) < CnxTime_Max?

Does this connection violate any circuitry rule?

Store the linked flight segments in a single connection file as a single connecting flight

End of OutboundFile?

End of InboundFile?

End of station list?

Return

(Figure 4.22: continued)
"DoubleConnectionBuilder" Subroutine

Read each connecting flight record in a "single connection flight schedule file":
For I=1 to EOF: Cnx_Sng(i)

Read each flight segment record in a "direct flight schedule file":
For J=1 to EOF: Flight_Link(j)

Connect direct flights:
( Flight # of Flight_Inb(k) = flight # of Flight_Oub(m) ) ?

Store the linked flight segments in a double connection file as a 2-stop direct flight

((Destination of SngCnx_Oub(i))=Origin of Flight_Link(j)) And
(Origin of SngCnx_Inb(i)=Destination of Flight_Link(j)) And
(Destination of SngCnx_Inb(i)=Destination of Flight_Link(j)) ?

Connect flight segments based on pre-set minimum & maximum connecting times:
(CnxTime_Min < (Departure time of Flight_Oub(i) + arrival time of Flight_Inb(i)) < CnxTime_Max )?

Does this connection violate any circuitry rule?

Store the linked flight segments in a double connection file as a double connecting flight

End of direct flight segments file?

End of single connection file?

Return
CHAPTER 5

DEVELOPMENT OF FLIGHT SCHEDULE EVALUATION SYSTEM

Once the initial airline schedules are developed, the process of evaluating the schedules typically involves the entire airline. Since tactical decisions related to the implementation of the schedule are the responsibility of various operating departments, each of these operating departments is responsible for the evaluation of the aspects of the draft which pertain to them. Since the most basic and important usage of the developed schedule is to sell seats, it is very important for an airline to determine which product attributes passengers prefer when they choose one airline or a single flight over another airline or flight. It has long been conceded that passenger preference for particular flight paths is influenced consciously or unconsciously by many factors including:

1) type of aircraft operating over the path (flight itinerary);
2) number of en route stops on through flights;
3) number of connections on connecting flights;
4) frequency of service in true O&G markets;
5) time of day passengers wish to depart from the origin airport and arrival times at the destination.
Therefore, each department that evaluates the developed schedule must carefully analyze the pertinent attributes of the flight schedule. The main objective of such evaluation is to determine with some accuracy the revenues (in the case of this discussion, only passenger revenues are considered) that will accrue from flying the developed schedule and the costs that will be incurred in operating the developed schedule.

To forecast expected passenger revenues, the airline first has to forecast the number of passengers they will capture in all the origin and destination markets. Essentially the forecasting procedure consists of a “traffic allocation” algorithm for the assignment of origin and destination traffic to alternative paths in the given schedule in proportion to each path’s relative attractiveness. Once the airline determines the number of passengers who will be flying during a specified scheduling period, passenger revenues can be estimated based on the fare level that each passenger will pay. As stated in the previous chapter, this system only considers the average fare that is computed based on the equation generated by a linear regression of the data from the U.S. Department of Transportation. This fare determination model is a function of the distance of each origin-destination market. Figure 5.1 shows the overall process of this flight schedule evaluation system.
Flight Schedule Evaluation System

"TrueODGeneration" subroutine:
This routine generates all the city pairs served by all the airlines in the system and saves them in a file, TrueODFile.

Read each true O-D city pair in "TrueODFile":
For I=1 to EOF: CityPair(i)

Market Share Determinant module:
This module determines attractiveness scores of all the flight services existing in a selected city pair, CityPair(i), and a market share of each airline in CityPair(i). The attractiveness score of each flight service and the market share of each airline are then saved in a file, MarketShareFile.

End of city pair list?
No
Yes

Passenger Allocation module:
This module allocates passengers to each nonstop flight segment by each passenger group's true origin-destination city pair and computes each passenger type's revenue contribution to total revenues of a nonstop flight segment. This module separates the total revenues of a nonstop flight segment into local revenue, upline revenue, and downline revenue.

Weekly one-way passenger demand database

Revenue Generator module:
This module determines revenues by flight segment, true O-D market, individual aircraft, fleet of the same aircraft type, and an airline's entire network

Cost Generator module:
This module generates operating costs by flight segment, individual aircraft, fleet of the same aircraft type, and an airline's entire network

Segment & network based profitability analysis

Return

Figure 5.1: Flight schedule evaluation system
5.1 Definition of True Origin & Destination (O&D) Market

A by-product of the hub complex is that it enables connecting traffic (that competes with the local traffic on the inbound and outbound flights) to flow across the hub city. These connecting passengers who are sitting on aircraft seats of a particular nonstop flight segment may not have anything to do with either the origin airport nor the destination airport. Therefore, revenues generated by these connecting passengers are not directly associated with this particular nonstop flight segment; rather, the revenues generated by this non-local traffic is based on their actual origin and destination city pairs. This term, true origin and destination (O&D), is used to designate the one-way origin and destination city pair traversed by the passenger (regardless of the number of the flights or segments flown) within the airline's network. While some of these true O&D markets can be served by a nonstop direct flight, many of these markets can only be served with through (direct) flight itineraries that involve one or more en route stops. The fact that there exist this combination (mix) of different passenger types makes it very complicated to determine the exact revenue contribution of each passenger group to a nonstop flight segment.

![Traffic compositions on a nonstop flight segment](image)

*Figure 5.2 Traffic compositions on a nonstop flight segment*
Figure 5.2 illustrates this mix of passenger types on a flight segment. In this figure, a true O&D market for passenger type 1 (local traffic for Flight #2) is a city pair between PHX and CMH because these passengers exit the airline’s network system once they arrive at CMH. However, the true O&D markets for passenger types 2 and 3 include only either a departing or arriving airport of the flight segment, Flight #2. The last passenger type, traveling from LAX to EWR, have nothing to do with either PHX or CMH, even though they have to stop at these airports.

A flowchart shown in Figure 5.3 shows algorithms implemented in the system to determine all the true O&D markets that can be served by integrated network systems formed by all the airlines in the system.

Figure 5.3: Algorithm of true O&D market generation

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5.2 Market Share Determinant Module

Forecasting an airline's market share is a very complicated process because it must take into consideration numerous variables. The most important determinants in computing the market share of each airline between any given city pair are the type of flight service an airline is offering (nonstop, one-stop direct, multi-stop direct, intraline connection, or intraline connection), flight frequency, fare levels, types of aircraft (wide-body jet, narrow-body jet, regional jet or turbo-prop), and time of day passengers prefer to depart and arrive. In addition to these variables, there are other factors that influence the attractiveness of an airline, such as departure and arrival airports, an airline's image of customer service and safety, frequent flyer programs, and so on. Even though there are several models developed to determine the market share of an airline, the most popular and widely used one in the airline industry is called the “Quality and Service Index (QSI).” The author has come up with a significantly modified QSI model to be integrated in this system to determine the attractiveness of each flight service and the market share of each airline in any given city pair. The simplified basic equations are given as:

1) Attractiveness Score = Frequency share × Aircraft type × Time of day variation factor

2) Attractiveness of a selected flight

\[
\text{Attractiveness score of selected flight} = \frac{\sum \text{(Scores of all flight services offered by our airline and competitors between selected city pair)}}{\sum \text{(Scores of all flight services offered by our airline and competitors between selected city pair)}}
\]

3) Market share of an airline between selected city pair

\[
= \frac{\sum \text{(Scores of all flight services offered by our airline between selected city pair)}}{\sum \text{(Scores of all flight services offered by our airline and competitors between selected city pair)}}
\]

Figure 5.4 shows a detailed algorithm implemented in the system to determine market shares of all the airlines in the system.
Start market share determinant module

Read each true O-D city pair in "TrueODFile":
For I=1 to EOF: CityPair(i)

Initialization:
-- to determine the sum of a total attractiveness score of all the airlines in a selected true O-D market, CityPair(i):
  - Weight_All(i) = 0

Read each airline's two letter code in "AirlinesListFile":
For J=1 to EOF: Airline(j)

Initialization:
-- to determine the sum of a total attractiveness score of a selected airline, Airline(j), in a selected true O-D market, CityPair(i):
  - Weight_Airline(j) = 0

Read each Airline(j)'s nonstop flight segment in a nonstop flight segment file:
For K=1 to EOF: Flight_Link(k)

No

(Origin of CityPair(i)=Origin of Flight_Link(k)) And (Destination of CityPair(i)=Destination of Flight_Link(k))?

Yes

Retrieve all the attributes of this nonstop flight segment, such as departure/arrival times and aircraft type, and compute the attractiveness of this flight service (Weight of Flight_Link(k)) based on its QSI weights.

Weight_All(i) = Weight_All(i) + Weight of Flight_Link(k);
Weight_Airline(j) = Weight_Airline(j) + Weight of Flight_Link(k)

No

End of flight link list?

Yes

Figure 5.4: Market share determinant module
Read each Airline(i)'s one-stop and multi-stop direct and connecting flight service in a connecting schedule file*:

For K=1 to EOF: ● Flight_Chain(k)

*(A direct flight that has at least one stop in its itinerary between its origin and destination airports is saved in a connecting schedule file)

(Origin of CityPair(i) = Origin of Flight_Chain(k)) And (Destination of CityPair(i) = Destination of Flight_Chain(k))

Retrieve all the attributes of this flight itinerary, such as departure/arrival times, aircraft types, type of this flight service (direct or connection), and a number of stops for this chain, and compute the attractiveness of this flight service (Weight of Flight_Chain(k)) based on its QSI weights.

● Save this data in "FlightQSIFile"

Save Weight_All (i) as an array of each O-D market:

● Weight_All (i) = Weight_All (i) + Weight of Flight_Link(k);

Save Weight_Airline (j) as an array of each airline:

● Weight_Airline (j) = Weight_Airline (j) + Weight of Flight_Link(k)

End of connecting schedule file?

Yes

End of AirlinesListFile?

Yes

Read each airline’s two letter code in "AirlinesListFile":

For J=1 to EOF: ● Airline(j)

Compute & save market share of each airline:

● MarketShare(j) = Weight_Airline (j) / Weight_All (i)

End of AirlinesListFile?

Yes

End of TrueODFile?

Yes

Return

(Figure 5.4: continued)
Tables 5.1, 5.2, and 5.3 list the factors which are implemented in the attractiveness equation. The weight value of each category listed in the table can be easily modified.

<table>
<thead>
<tr>
<th>Frequency Share</th>
<th>Aircraft Type QSI</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Flight</td>
<td>Intra-Cnx.(^1)</td>
<td>Inter-Cnx.</td>
</tr>
<tr>
<td># of Stops</td>
<td># of Stops</td>
<td># of Stops</td>
</tr>
<tr>
<td>0</td>
<td>3.2</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0.8</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
<td>others</td>
</tr>
<tr>
<td></td>
<td></td>
<td>others</td>
</tr>
</tbody>
</table>

\(^1\) Single intra-connections

- # of stops = 1
  - Combination of two nonstop direct flights
- # of stops = 2:
  - Combination of a nonstop direct flight and one-stop direct flight
- # of stops = 3:
  - Combination of a nonstop direct flight and two-stop direct flight or
  - Combination of two one-stop direct flights

Table 5.1: QSI weight systems for frequency share and aircraft types

<table>
<thead>
<tr>
<th>Penalty</th>
<th>Multi-stop direct</th>
<th>Connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance &lt; 300 miles</td>
<td>45%</td>
<td>90%</td>
</tr>
<tr>
<td>300 miles ≤ Distance &lt; 800 miles</td>
<td>25%</td>
<td>50%</td>
</tr>
<tr>
<td>800 miles ≤ Distance &lt; 1,500 miles</td>
<td>13%</td>
<td>30%</td>
</tr>
<tr>
<td>1,500 miles ≤ Distance</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 5.2: Penalties applied to connecting flights and multi-stop direct flights for short-haul

<table>
<thead>
<tr>
<th>Time Range</th>
<th>Score for departure time</th>
<th>Score for arrival time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00 – 5:59</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>6:00 – 7:59</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>8:00 – 9:59</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>10:00 – 11:59</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>12:00 – 13:59</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>14:00 – 15:59</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>16:00 – 17:59</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>18:00 – 19:59</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>20:00 – 21:59</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>22:00 – 23:59</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 5.3: QSI weight systems for time of day variation scale
5.3 Passenger Allocation Module

This module allocates weekly passenger demand between all the city pairs to each flight and identifies the types of passengers on all nonstop flight segments. On any given nonstop flight segment, there are usually more than one type of passenger, as discussed in a previous section. Identifying each of these passenger types is very critical in evaluating an airline schedule because the amount of revenue each passenger is contributing to any particular nonstop flight segment is significantly different. In this passenger allocation module, some revenue management concepts, such as spill and recapture, apply to flights that have more passenger demands than available seats (known as a “closed flight”). Because the allocation is not performed simultaneously for all possible paths and all markets that contribute traffic, the process of allocating the demand to each candidate for through or connecting flight path cannot be accomplished in a single step. Therefore, loading each passenger on a flight is carried out by applying the incremental loading processes. Following equations show relationships between a total load factor and each passenger group’s load factor contribution:

\[
L.F.\text{ Contribution} = \frac{\# \text{ of pax. of a particular true O & D pair segment}}{\# \text{ of Seats on aircraft}}
\]

\[
Actual \text{ Onboard L.F.} = \frac{\text{Total \# of all pax. on board}}{\# \text{ of Seats on aircraft}} = \sum \left( \frac{L.F. \text{ Contribution by each true O & D pair}}{\# \text{ of Seats on aircraft}} \right)
\]

A flowchart in Figure 5.5 illustrates subroutines embedded in the passenger allocation process. Flowcharts that show detailed algorithms of each subroutine of the passenger allocation process are included in the appendix.
"PassengerTypeGeneration" subroutine:

This subroutine determines the types of passengers (categorized by each passenger's true O-D market) who will be on board a selected flight segment on a specific day of the week.

"ComputeTotalQSI" subroutine:

This subroutine computes the total QSI weights of a selected city pair, taking into consideration all the flight services (nonstop, one-stop & multi-stop direct flights and intraline & interline connections) offered by all the airline in this true O-D market.

"ComputeFlightQSI" subroutine:

This subroutine identifies all the flight itineraries that comprise a selected flight segment and determines a QSI weight of each flight service to determine an attractiveness score of each flight service (attractiveness score of the flight service = \( \text{QSI_Flight} \div \text{QSI_Sum} \)). This subroutine then performs an initial passenger allocation process by determining the number of passengers who will be on board.

"OnboardPassengerAllocationProcess" subroutine:

This subroutine performs iterative processes to allocate passenger demands to each flight segment in the order of the amount of each passenger type's revenue contribution to an airline's network system, taking into consideration spill and recapture algorithms. There are three iterations involved with this routine and the passenger type which contributes the highest revenue to the airline's entire network system has the highest priority during this iterative allocation process.
Start Passenger Allocation Module

Read each nonstop flight segment in a weekly nonstop flight segment file:
For K=1 to EOF: → Flight_Link(k)

"PassengerTypeGeneration" subroutine:
This subroutine determines the types of passengers (categorized by each passenger's true O&D market) who will be on board a selected flight segment on a specific day of the week, Flight_Link(k).

3 main categories of passenger traffic types:
1. local traffic: those who are flying only this segment, Flight_Link(k)
   → nonstop direct flight
2. through traffic: those who are flying this segment as a part of their entire flight itineraries that require no changes in aircraft at any of the en-route stops
   → one- or multi-stop direct flight
3. connecting traffic: those who are flying this segment as a part of their entire flight itinerary in conjunction with one or more other flights
   → single or double connecting flight

Store passenger types on Flight_Link(k) in a file, PaxTypeFile
[Data fields: Flight_Link(k), Origin, Destination]

Read each true O-D city pair in "PaxTypeFile":
For M=1 to EOF: → PaxType(m)

"ComputeTotalQSI" subroutine:
This subroutine computes the total QSI weights of a selected city pair, PaxType(m), taking into consideration all the flight services (nonstop, one-stop, and multi-stop direct flights, and intraline and interline connections) offered by all the airline in this true O&D market. → QSI_Sum(m)

"ComputeFlightQSI" subroutine:
This subroutine identifies all the flight itineraries that comprise a selected flight segment, Flight_Link(k), and determines a QSI weight of each flight service to determine an attractiveness score of each flight service (attractiveness score of the flight service = QSI_Flight + QSI_Sum(m)). This subroutine then performs an initial passenger allocation process by determining the number of passengers who will be on board, Flight_Link(k).

Figure 5.5: Passenger allocation module
Store initial passenger allocation data in "PaxAllocationFile"

No

End of PaxTypeFile?

Yes

Store Flight_Link(k)'s initial aggregate passenger allocation data in "FlightPaxTypeFile"
[data fields: Index_First, Index_Last, Flight_Link(k), Seats_AC, number of passenger type, number of passengers allocated (passenger demand for this flight segment)]

No

End of weekly nonstop flight segment list*?

Yes

"OnboardPassengerAllocationProcess" subroutine:
This subroutine performs iterative processes to allocate passenger demands to each flight segment, Flight_Link(k), in the order of the amount of each passenger type's revenue contribution to an airline's network system, taking into consideration spill and recapture algorithms. There are three iterations involved with this routine, and the passenger type which contributes the highest revenue to the airline's entire network system has the highest priority during this iterative allocation process.

Return

*Note: The system treats each flight segment on a specific day of the week separately, even though the same flight segment (the same flight number, the same departure and arrival times, and the same type of aircraft) is flown every day (daily flight) during a given flight cycle. This logic ensures that the system is able to handle a daily fluctuation of passenger demands for a particular flight segment. This algorithm is made possible by assigning a specific flight identification code that can identify a specific day of the week when this flight segment is flown.

(Figure 5.5: continued)
Examples of passenger mix problems

Case 1: UA 123
Flight itinerary: LAX → ORD
Aircraft: B737-400 (# of seats = 150)

<table>
<thead>
<tr>
<th>Types of Pax.</th>
<th>Allocated Pax. Demand</th>
<th>% of Each Pax. Type</th>
<th>Actual Pax. on-board</th>
<th>L.F. Contribution of Each Pax. Type</th>
<th># of Pax. Spilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAX → ORD</td>
<td>120</td>
<td>100%</td>
<td>120</td>
<td>80%</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>120</td>
<td>100%</td>
<td>120</td>
<td>80%</td>
<td>0</td>
</tr>
</tbody>
</table>

1. by true origin - destination of passenger's trip itinerary
2. # of passengers allocated to this particular flight
3. (Allocated pax. demand of a single pax. type) ÷ (Total allocated pax. demand);
   ((120 ÷ 120) x 100% = 100%)
4. Actual # of passengers on board
5. Actual pax. on-board ÷ # of seats (= (120 ÷ 150) x 100%)
6. # of pax. who wanted to take this flight, but were forced to take other flights of either our airline or competitors or cancel their trips because there are not enough available seats on this flight (Demand > Supply). Some of the spilled passengers are considered to be the lost revenues.

This particular flight happens to serve only local traffic passengers, who are traveling from LAX to ORD, because this nonstop flight segment is not a part of either a through flight or connecting flight.

Case 2: UA 152
Flight itinerary: LAS → ORD
Aircraft: B757-400 (# of seats = 200)

<table>
<thead>
<tr>
<th>Types of Pax.</th>
<th>Allocated Pax. Demand</th>
<th>% of each Pax. Type</th>
<th>Actual Pax. on-board</th>
<th>L.F. contribution of each Pax. Type</th>
<th># of Pax. Spilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAS → ORD (local traffic)</td>
<td>120</td>
<td>40.7%</td>
<td>73</td>
<td>36.5%</td>
<td>47</td>
</tr>
<tr>
<td>LAS → CMH (through traffic)</td>
<td>100</td>
<td>33.9%</td>
<td>61</td>
<td>30.5%</td>
<td>39</td>
</tr>
<tr>
<td>LAS → LHR (connecting traffic)</td>
<td>75</td>
<td>25.4%</td>
<td>46</td>
<td>23%</td>
<td>29</td>
</tr>
<tr>
<td>Total</td>
<td>295</td>
<td>100%</td>
<td>180</td>
<td>90%</td>
<td>115</td>
</tr>
</tbody>
</table>

1. by true origin - destination of passenger's trip itinerary
2. # of passengers allocated to this particular flight
3. (Allocated pax. demand of a single pax. type) ÷ (Total allocated pax. demand)
4. Actual # of passengers on board
5. Actual pax. on-board ÷ # of seats
6. # of Spilled Pax. = Allocated pax. demand − Actual pax. on-board;
   = 100 − 61 = 39 for LAS → CMH pax. type
Determination of average one-way fare

To estimate an average one-way fare of all the true O&D markets systematically, the data set which contains average fares of 1000 city pairs was plotted against the distance between each true O&D city pair's origin and destination cities. The linear regression was then performed to generate an equation that can be implemented in the system. Figure 5.6 shows the chart that represents this function.

Distance Line Fit Plot (Average)
\[ \text{Fare} = 97.298 + 0.07249 \times \text{Distance} \]

* Source: U.S. Department of Transportation (January 1998)

Figure 5.6: Average one-way fare level vs. distance (Second Quarter 1997)
**Fare prorating algorithm based on trip distances**

As discussed in the Passenger Allocation Module section, the total revenues of any nonstop flight segment is the sum of the revenues contributed by local passengers, up-line and down-line connecting passengers, and through passengers. To determine revenue contributions by both up-line and down-line passengers, the fare is prorated based on the distance of the segment. This algorithm is discussed below, using a sample network shown in Figure 5.7.

![Figure 5.7: Sample network](image)

* Let’s assume that the following figures represent average one-way fares obtained using the equation shown in Figure 5.7:

- CMH → CLE: Fare = $182
- CLE → PHL: Fare = $225
- CMH → PHL: Fare = $232
- ORD → CLE: Fare = $213
- ORD → PHL: Fare = $274
* # of assumed passengers on board (shown by each passenger type)

<table>
<thead>
<tr>
<th>CO 100</th>
<th>CO 200</th>
<th>CO 400</th>
<th>HP 300</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMH → CLE</td>
<td>50</td>
<td>CLE → PHL</td>
<td>60</td>
</tr>
<tr>
<td>CMH → PHL</td>
<td>30</td>
<td>CMH → PHL</td>
<td>30</td>
</tr>
<tr>
<td>ORD → PHL</td>
<td>40</td>
<td>ORD → PHL</td>
<td>40</td>
</tr>
<tr>
<td><strong>Total # of Pax</strong></td>
<td><strong>80</strong></td>
<td><strong>130</strong></td>
<td><strong>90</strong></td>
</tr>
</tbody>
</table>

* Actual revenues for each nonstop flight segment:

**CO 100:**
- CMH → CLE; ($182)×(50) = $9,100
- CMH → PHL; (120/(120+370))×($232)×(30) = $1,704
  
  Total revenue of **CO 100** = $9,100 + $1,704 = $10,804

**CO 200:**
- CLE → PHL; ($225)×(60) = $13,500
- CMH → PHL; (370/(120+370))×($232)×(30) = $5,256
- ORD → PHL; (300/(300+370))×($274)×(40) = $4,907
  
  Total revenue of **CO 200** = $13,500 + $5,256 + $4,907 = $23,663

**CO 400:**
- ORD → CLE; ($213)×(50) = $10,650
- ORD → PHL; (300/(300+370))×($274)×(40) = $4,907
  
  Total revenue of **CO 400** = $10,650 + $4,907 = $15,557

**HP 300:**
- CMH → PHL; ($232)×(120) = $27,840
  
  Total revenue of **HP 300** = $27,840

### 5.4 Revenue Generator Module

Once the average one-way fare of a true O&D market is estimated and fares are prorated, passenger revenues can be determined. This section shows a flowchart (Figure 5.8) that explains how the passenger revenues can be represented in various ways in the system.
Start Revenue Generator Module

Inputs:
- Read data stored in files generated in the "Passenger Allocation Module"

Generate revenues of each flight segment
- Generate revenues of each direct flight's entire itinerary (chain of flight segments using the same flight number)
- Generate revenues of each aircraft (based on individual aircraft's tail number)
- Generate revenues of each aircraft type (based on the fleet of the same aircraft type)
- Generate revenues of each true origin-destination market (total revenues generated by all flight services offered between two cities)

Generate revenues of the airline's entire network system

Return

Figure 5.8: Revenue generator module
5.5 Cost Generator Module

Total costs are divided into the following three categories in this system: aircraft operating cost, aircraft ownership cost, and non-operating cost (system cost). Aircraft operating cost, which consists of labor (cockpit & cabin crews) cost, fuel cost, and maintenance cost, varies by each aircraft type and is allocated by block hour. Aircraft ownership cost also varies by aircraft type and is defined for each aircraft. Analysis determined that non-operating cost is about 55% of the total operating cost for an airline.

\[ \text{System Cost} = 1.2 \times (\text{Aircraft Operating Cost} + \text{Ownership Cost}) \]

Unlike revenues, costs cannot be represented by true origin-destination, but can be computed by nonstop flight segment, direct flight, aircraft, and system network. Figure 5.9 illustrates the detailed algorithms that are implemented in the system to determine each part of an airline's total operating costs. It also shows the overall process of determining an airline’s total operating costs. Finally, Figure 5.10 illustrates how to compute aircraft ownership costs.
Start Cost Generator Module

"ACLeaseCostDeterminant" subroutine

Read each nonstop flight segment in a weekly nonstop flight segment file:
For K=1 to EOF: Flight_Link(k)

Aircraft_Link = aircraft type assigned to Flight_Link(k)
BlkHr_Link = block hour of a selected flight segment, Flight_Link(k)

Aircraft direct operating cost database

Retrieved direct operating cost index (per block hour) of an aircraft type, Aircraft_Link:
1. DOC_Labor_BH = labor(crew) cost per block hour
2. DOC_Fuel_BH = fuel cost per block hour
3. DOC_Main_BH = maintenance cost per block hour
4. DOC_Other_BH = other direct operating cost per block hour

Compute direct operating cost of a selected segment, Flight_Link(k):
1. DOC_Labor_Link = DOC_Labor_BH × BlkHr_Link
2. DOC_Fuel_Link = DOC_Fuel_BH × BlkHr_Link
3. DOC_Main_Link = DOC_Main_BH × BlkHr_Link
4. DOC_Other_Link = DOC_Other_BH × BlkHr_Link

Total direct operating cost of a selected segment, Flight_Link(k):  
DOC_Link(k) = DOC_Labor_Link + DOC_Fuel_Link + DOC_Main_Link + DOC_Other_Link

Total indirect operating cost of a selected segment, Flight_Link(k):
IOC_Link(k) = 1.612 × DOC_Link(k)

Figure 5.9: Cost generating module
Read data in ACLeaseCostFile:
For F=1 to EOF: \( ACType(f); LeaseCost\_BH(f) \)

\((\text{Aircraft\_Link} = ACType(f)) \) ?

Yes

Compute an aircraft operating lease cost of a selected link, Flight\_link( k):
\( \text{LeaseCost\_Link}(k) = \text{LeaseCost\_BH}(f) \times \text{BlkHr\_Link} \)

Compute total operating costs of a selected link, Flight\_link( k):
\( \text{Costs\_Link}(k) = \text{DOC\_Link}(k) + \text{IOC\_Link}(k) + \text{LeaseCost\_Link}(k) \)

Save all the cost data in a file, "FlightLinkCostFile"

End of weekly nonstop flight segment list? 

Yes

Inputs:
\( \text{Read data stored in "FlightLinkCostFile"} \)

Generate operating costs of each flight segment

Generate operating costs of each aircraft (based on individual aircraft's tail number)

Generate operating costs of each direct flight's entire itinerary (chain of flight segments using the same flight number)

Generate operating costs of each aircraft type (based on the fleet of the same aircraft type)

Generate operating costs of the airline's entire network system

Return

(Figure 5.9: continued)
"ACLeaseCostDeterminant" subroutine

Read data in FleetInfoFile generated in the "Aircraft Rotation Module":
For F=1 to EOF: ➔ ACType(f)

Retrieved input data of an aircraft type, ACType(f):
➔ No_AC(f) = a total number of aircraft of a selected aircraft type, ACType(f)
➔ Dist_Total(f) = a total distance that all the aircraft of ACType(f) has flown in a week
➔ BlkHrs_Total(f) = a total block hours that ACType(f), has flown in a week

Aircraft direct operating cost database

Retrieved input data of an aircraft type, ACType(f):
➔ LeaseCost_Month(f) = a monthly leasing cost of a selected aircraft type, ACType(f) (for a single aircraft)

Compute a weekly leasing cost of a single aircraft of ACType(f):
➔ LeaseCost_Week(f) = LeaseCost_Month(f) / 4.3

Compute a weekly leasing cost of all the aircraft of ACType(f):
➔ TotalLeaseCost_Week(f) = LeaseCost_Week(f) × No_AC(f)

Compute leasing cost of ACType(f) per block hour:
➔ LeaseCost_BH(f) = TotalLeaseCost_Week(f) / BlkHrs_Total(f)

Save the leasing cost data in a file, "ACLeaseCostFile"
[data fields: ACType(f), LeaseCost_BH(f)]

End of FleetInfoFile? ➔

Yes ➔ Return
No ➔ Aircraft ownership cost (operating lease cost for this system) mainly depends on the number of aircraft of the same type of aircraft.

Figure 5.10: Determining aircraft leasing costs
6.1 Summary of Dissertation

As emphasized throughout the dissertation, in order to increase profitability and gain a competitive edge, airlines have been developing and investing in scheduling decision support tools. While flight scheduling systems were developed and marketed by major airlines to aid their schedule planning, none of them has been available as a learning and a teaching tool. Most of these systems require very expensive and hard-to-use UNIX-based workstations and enormous amounts of detailed data. These particular hardware and data requirements alone can place barriers on the usage of these systems. In addition to these very expensive and complicated computer hardware requirements, the systems themselves are very expensive and difficult to use. Based on some of these limitations, these flight scheduling systems have been mostly available to major airlines. Many smaller airlines worldwide cannot afford to use such systems, not just because they are too expensive to implement in their existing systems, but also these systems are too complicated to use for the smaller airlines' existing personnel. Simply put, smaller airlines have not been able to afford, maintain, or utilize such systems with efficiency or effectiveness.
The dissertation described the development of a PC-based computerized airline schedule analysis and planning system that is equipped with a menu-driven graphical user interface. The main objective was to develop models and a system that can be used as a learning tool for students and entry-level practitioners in the area of airline schedule/route/fleet planning. This system allows its users to learn the intricacies of the airline scheduling practice — not only the basics, such as operational feasibility, but also the more complex features of sensitivity and the interaction of numerous key variables. Since planning an airline schedule is a very complicated task, the simplified schedule planning paradigm shown in Figure 3.1 has been developed to aid understanding of scheduling and to make the task more accessible. Even though this system is not as sophisticated or complex as those developed by major airlines, it contains most of the components that are directly related to actual airline flight schedule planning and it includes development processes to be used as a learning tool. The system consists of a series of decision modules and subroutines that have to be solved to make the flight schedule operational. The following areas in the area of airline schedule planning have been studied and implemented in the system:

1) Development of airline’s direct flight schedule
2) Connection builder
3) Fleet assignment and aircraft rotation plan
4) Market share determinant module
5) Passenger allocation process
6) Airline passenger revenue and total operating cost structures
A significant contribution of this dissertation is that these separate subjects, all related to airline schedule planning, are integrated into a single system to develop and analyze comparatively smaller but nonetheless realistic flight schedules.

The system basically consists of major two sub-systems, as shown in Figure 3.1. The Flight Schedule Generation System creates an airline’s basic direct flight schedule and builds all the possible connecting paths (both intraline and interline connections). During this schedule generation process, the aircraft rotation module determines the number of aircraft, of each aircraft type needed, to operate the schedule. It also generates each individual aircraft’s weekly aircraft routing plan. Based on these complete flight schedules, the flight schedule evaluation system first determines a market share of each airline in the entire system. Then the system allocates passengers on each nonstop flight segment. This passenger allocation process involves identifying a different mix of passengers by their true O&D markets on all the nonstop flight segments. This procedure generates comprehensive data that can be used to generate estimated passenger revenues in a subsequent report generator module. Finally, the cost generator module computes an airline’s operating costs at various levels.

6.2 Future Work

Scheduling might be defined as the art of synthesizing a multiplicity of interrelated factors, such that a balanced pattern of flight segments yielding the maximum of some value (such as profit) emerges. Scheduling is the heart of the airline business. However, due to a large number of factors that have to be considered from the moment an airline initiates the schedule planning process to the last minute an aircraft takes off from a scheduled airport, the complexity of the scheduling process requires a system that...
takes into consideration all those decision factors and operating constraints. Developing such a system is a very difficult, if not impossible, task. For these reasons, the system developed here still lacks some components, even though every effort has been made to accommodate as many decision factors and operational constraints as possible (even at a rudimentary level) and still obtain detailed data which reflects actual airline operations as possible.

To improve the learning process by increasing the realism of the system, there are some modules and factors that can be studied further and implemented in the system. First of all, implementing an algorithm that considers more complete aircraft maintenance schedules in an aircraft rotation module would improve this system's credibility and reliability. As an initial solution to the aircraft maintenance scheduling problem, the current aircraft rotation algorithm can be modified by introducing a dummy aircraft string that can represent scheduled maintenance at a designated station. The aircraft routing schedule would then include a string that includes nodes designated as maintenance bases able to perform one or more regularly scheduled, required maintenance checks.

A second important aspect that needs to be investigated is determining revenues and costs. To begin with, it is necessary to incorporate demand elasticity that allows users to examine the influence of fare changes. Next, a more accurate and systematic method of applying yield management concepts would greatly improve the process of estimating passenger revenues. Finally, as mentioned in Chapter 1, the current system is capable of dealing with only the passenger traffic. However, many airlines carry a substantial amount of cargo traffic. Therefore, this system would be more realistic and viable if an algorithm were developed that could at least estimate the revenues generated
by carrying cargo traffic. As far as determining an airline's total operating costs is concerned, a more accurate cost data index, such as aircraft leasing costs or purchase costs, could boost the system's accuracy in performing a profitability analysis.

Third, extensions of this research related to developing a more accurate and comprehensive method to determine QSI weight values can help the system to better estimate the attractiveness of each flight. For example, even though the current system takes into consideration the importance of each flight's attractiveness level based on time-of-day variations, each market may have different distribution curves depending on the type of the destination. Moreover, since QSI weights are the basic index of each airline's market share and attractiveness score of each flight itinerary, and since these attributes are essential determinants of passenger preferences, obtaining more accurate QSI weights would significantly improve the overall result of the flight evaluation system. Specifically, the factors which could be included in the attractiveness equation are:

1) day-of-week preference
2) more sophisticated fare structure
3) airline images in terms of safety and customer service (branding)
4) frequent flyer program

Fourth, an area of potential improvement to the system would be to include some of decision variables that are out of an airline's control, such as bilateral agreements between countries and airports' slot constraints. These variables could be applied to the system as added constraints that must be applied when scheduling flights.
A fifth airline scheduling problem that should be addressed by the system is in the area of crew scheduling. However, accommodating this factor will probably require extensive and complete modification to the existing system. Assigning crew members is a very complicated process, and it involves numerous uncertain and unpredictable factors because of its dependence on equally unpredictable humans. Therefore, implementing crew scheduling tools in this system would be extremely difficult.

Further extensions to this research involve the system’s interfaces, particularly in the area of user interface capability with route maps. By adopting more sophisticated and intricate mapping software tools and methods in the system, the system could provide more direct interactive capabilities. For example, the route map system could be used as an input screen with route segment lines and airport nodes displayed interactively so that detailed operational and geographical information of a flight or airport could be accessed with a simple double-click. Not only would information about flights or airports be displayed, but the system would also show market information such as fares, passenger demand of a market represented by the line selected, on board load factors, a number of passengers spilled, segment revenues, and operating costs of a selected flight segment.

Some of the extensions suggested above only represent a fraction of the list of potential improvements to the system. Many more areas could be improved to obtain more accurate and realistic results. However, the author believes that the research that has led to the development of the current system can serve as a base for additional research in the area of airline scheduling and provide a framework for further development of an improved airline scheduling decision support system that can be easily implemented as a learning tool.
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2. Airline Network & Hub-and-Spoke Systems


3. Airline Revenue (Yield) Management


4. Airline Demand Forecasting and Market Share


5. Commercial Aircraft Technology


6. Airline Revenues and Costs


7. Airline Industry


Appendix

Supplementary Flowcharts to Chapter 5
"PassengerTypeGeneration" subroutine (Flight_Link(k))

Store local traffic type on Flight_Link(k) in PaxTypeFile:
  true origin = origin of Flight_Link(k);
  true destination = destination of Flight_Link(k)

Read airline's one-stop and multi-stop direct and connecting flight services in a connecting schedule file:
For N=1 to EOF: Flight_Chain(n)

Does Flight_Link(k) match any leg of a selected chain, Flight_Chain(n)?

Yes

Store through- and connecting traffic types on Flight_Link(k) in PaxTypeFile:
  true origin = origin (initiating airport) of Flight_Chain(n);
  true destination = destination (terminating airport) of Flight_Chain(n)

No

End of connecting schedule file?

Yes

Return

Figure A.1: Passenger type generation routine
Initialization:
- to determine the sum of a total attractiveness score of all the airlines in a selected true O-D market: \( \text{Weight}_\text{Sum}(m) = 0 \)

Read each airline's two letter code in "AirlinesListFile":
For \( N = 1 \) to EOF: \( \text{Airline}(n) \)

Read each Airline\((n)\)'s nonstop flight segment in a nonstop flight segment file:
For \( K = 1 \) to EOF: \( \text{Flight}_\text{Link}(k) \)

(Origin of PaxType\((m)\) = Origin of Flight_Link\((k)\)) And (Destination of PaxType\((m)\) = Destination of Flight_Link\((k)\))?

Yes

Compute QSI weights: \( \text{Weight}_\text{Sum}(m) = \text{Weight}_\text{Sum}(m) + \text{Weight of Flight}_\text{Link}(k) \)

No

End of flight link list?
Yes

Read each Airline\((n)\)'s one-stop and multisstop direct and connecting flight services in a connecting schedule file:
For \( K = 1 \) to EOF: \( \text{Flight}_\text{Chain}(k) \)

(Origin of PaxType\((m)\) = Origin of Flight_Chain\((k)\)) And (Destination of PaxType\((m)\) = Destination of Flight_Chain\((k)\))?

Yes

Compute QSI weights: \( \text{Weight}_\text{Sum}(m) = \text{Weight}_\text{Sum}(m) + \text{Weight of Flight}_\text{Link}(k) \)

No

End of connecting schedule file?
Yes

End of AirlinesListFile?
Yes

Return

Figure A.2: Computing total QSI routine
"ComputeFlightServiceWeight" subroutine

Data is retrieved to determine an attractiveness score of a flight service, FlightItinerary(i), which includes FlightLink(k) in its chain of flight legs which connect two nodes of a selected city pair that represents a particular passenger type, PaxType(m). Depending on the flight type of FlightItinerary(i), the relation between FlightLink(k) and FlightItinerary(i) can be represented as follows:

- a link to be analyzed: FlightLink(k)
  - originating node of FlightLink(k) = "O"
  - terminating node of FlightLink(k) = "D"
- True origin & destination of FlightItinerary(i) vary with each selected record.

**Case 1:** local traffic type of FlightLink(k)

- FlightItinerary(i) = nonstop service between "O" and "D"

**Case 2:** through or connecting traffic type of FlightLink(k)

- FlightItinerary(i) = 1-stop or 2-stop service
- FlightLink(k) can be either a leg that connects two en route stops of a chain that represents FlightItinerary(i), or a leg that connects an en route stop node and either an originating or terminating node of FlightLink(k).

**Input:**
Data saved in "FlightQSIFile" generated in "Market Share Determinant" module

**Data fields of "FlightQSIFile"**
- true O-D market (true origin-destination airports), type of flight service (direct/connect), detail of flight itinerary data (flight legs, stops, departure/arrival times, aircraft type, distance and block hour of each leg, total distance and total block hours, etc.), QSI weights (frequency/aircraft/TOD(time-of-day variation)), & total attractiveness score

**Figure A.3: Computing flight service weight routine**

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Read each record in "FlightQSIFile" generated in "Market Share Determinant" module:
For \( t = 1 \) to EOF

Is FlightLink(\( k \)) a part of a flight chain, FlightItinerary(\( i \))?

No

Yes

Compute an attractiveness score of each selected flight service, FlightItinerary(\( i \)) and allocate passenger demands for a true origin-destination city pair of FlightItinerary(\( i \)) to a nonstop flight segment, FlightLink(\( i \)):
- Attractiveness score (share of this service) = total QSI weight of FlightItinerary(\( i \)) + QSI_Sum(\( m \))
- Allocated passengers = Attractiveness score \( \times \) passenger demand of a selected market

Compute revenue contribution of a passenger type of FlightItinerary(\( i \)) to a selected nonstop flight segment, FlightLink(\( k \)):
- Average one-way fare generated by this passenger type is prorated based on the relationship between the total distance of FlightItinerary(\( i \)) and each leg's distance
- Prorated fare for FlightLink(\( k \)) of the total fare paid by a passenger of FlightItinerary(\( i \)) = \([\text{One-way fare of true O-D (FlightItinerary(\( i \)))] \times \frac{\text{distance of FlightLink(\( k \))}}{\text{total distance of FlightItinerary(\( i \))}}\]

Save all the information retrieved from FlightQSIFile and all the values computed in this routine in a file, PaxAllocationFile. For each record, an index number should be assigned (starting from 1) and saved.

No

End of FlightQSIFile?

Yes

Return

(Figure A.3: continued)
Read each record in "FlightPaxTypeFile":
For I = 1 to EOF

Retrieved data fields of "FlightPaxTypeFile"
FlightLinkId(i) = identification code of a flight leg
Seats(i) = number of seats of an aircraft assigned to FlightLinkId(i)
No_PaxType(i) = number of passenger type on FlightLinkId(i)
Index_First(i) = first index number of passenger type that are associated with FlightLinkId(i)
Index_Last(i) = last index number of passenger type that are associated with FlightLinkId(i)
Pax_Allocated(i) = number of passenger demand allocated in a previous routing

Initialization: A = 0; dummyIndex = No_PaxType(i)

Read each record in "PaxAllocationFile":
For J = Index_First(i) to Index_Last(i)

Save retrieved data as array elements:
arrIndexNo(a) = IndexNo(j)
arrOWFare(a) = OWFare_TrueOD(j)
arrPaxAllocated(a) = PaxAllocated(j)

End of PaxAllocationFile (J = Index_Last(i))?

Sort the saved arrays in the order of descending fare level:
av(a) = 1 to (Index_Last(i) - Index_First(i) + 1)
arrOWFare(a); arrIndexNo(a); arrPaxAllocated(a)

Perform the first iteration of a passenger allocation process:
- Determine the number of passengers who will be on board by each passenger type
- Fill the seats on an aircraft of each flight segment in the order of each passenger type's revenue contribution level to an airline's network

Figure A.4: On board passenger allocation processing routine
Initialization: \( \text{Seats Remain} = \text{Seats AC} \times \text{LFCF} \)

Read data elements of the saved arrays:
For \( J = 1 \) to dummyIndex

\[
\begin{align*}
\text{arrPaxAllocated}(j) &< \text{Seats Remain}? \\
\text{arrPaxOnboard}(j) &\geq \text{Seats Remain} \\
\text{arrPaxOnboard}(j) &= \text{arrPaxAllocated}(j)
\end{align*}
\]

\( \text{Seats Remain} = \text{Seats Remain} - \text{arrPaxOnboard}(j) \)

End of an array (\( J = \text{dummyIndex} \)?)

End of FlightPaxTypeFile?

Perform the second iteration of a passenger allocation process:

- During the 1st iteration, seats on each flight segment were filled based on each passenger type's revenue contribution level, but the process of each flight segment was performed independently. This can result in possible imbalances of the number of passengers of the same passenger type among different flight segments that they have to fly in sequence to reach their final destination.
- During the second iteration, all the flight segments are re-evaluated and passengers are re-allocated to balance all flight segments.

(Figure A.4: continued)
Read each record in "PaxAllocationFile" :
For I=1 to EOF

Has a record been processed in connection with a previous record?

Yes

No

Data fields to be retrieved:
• assign dummy variables to flight segments that constitute a flight chain (itinerary) of a particular true O-D market
(Note that the number of legs allowed to form a single chain is 3.)
• dummyFlight1 = FlightSegmentId1(I)
dummyFlight2 = FlightSegmentId2(I)
dummyFlight3 = FlightSegmentId3(I)

Data fields to be retrieved: k=1
• save a number of passengers on board on a selected flight segment and an index number of this record as first elements of arrays
• dummyPaxOnboard(k) = Pax_Onboard(I); dummyIndex(k) = Index(I)

Read each record in "PaxAllocationFile" :
For J=I to EOF

[(dummyFlight1 = FlightSegmentId1(J)) And
(dummyFlight2 = FlightSegmentId2(J)) And
(dummyFlight3 = FlightSegmentId3(J))]

Yes

Update arrays: k=k+1 (outbound limit (maximum k value) of arrays is 3)
• dummyPaxOnboard(k) = Pax_Onboard(J); dummyIndex(k) = Index(J)

No

End of PaxAllocationFile (inner-loop)?

Yes

(Figure A.4: continued)
Select the smallest value of dummyPaxOnboard(t)'s and use this value as the number of passengers of this passenger type on all the flight segments (maximum of 3 segments).

Update PaxAllocationFile

No End of PaxAllocationFile (outer-loop)?

Yes

Perform the third iteration of a passenger allocation process.

In this final iteration stage, some of local traffic demands spilled in the previous stages will be recaptured if a flight segment has not been closed.

Read each record in "FlightPaxTypeFile":
For I=1 to EOF

Initialization:
dummyPaxOnboard_Sum = 0
dummyRevenue_Link = 0

Read each record in "PaxAllocationFile":
For J=Index_First(i) to Index_Last(i)

Determine if selected traffic is a local passenger type:
org. & dest. airports of a link being analyzed = true O-D airports of a pax. type?

Yes

Determine if there are any spilled passengers:
Pax_Allocated(j) > Pax_Oboard(j)?

No

Yes

(Figure A.4: continued)
Data fields to be retrieved: assign dummy variables
- dummyIndex_Link = Index_No(i)
dummyPaxSpilled = Pax_Allocated(i) - Pax_Onboard(i)
dummyOWFare_Link = OWFare_Link(i)

Update total number of passengers on board and total revenues of a selected link:
dummyPaxOnboard_Sum = dummyPaxOnboard_Sum + Pax_Onboard(i)
dummyRevenue_Link = dummyRevenue_Link + (Pax_Onboard(i) x OWFare_Link(i))

Determine if there are any empty seats:
- [dummyPaxOnboard_Sum < Seats_AC(i)]?

Seats_Remain = Seats_AC(i) - dummyPaxOnboard_Sum
Seats_Remain = 0

Determine if the number of remaining empty seats is greater than restricted number of seats by LFCF:
- Seats_Remain > (Seats_AC - (Seats_AC x LFCF))?

[Seats_Remain ≥ dummyPaxSpilled]?

Case 1: enough empty seats to recapture all the spilled local passengers
- dummyPax_Addition = dummyPaxSpilled;
dummyRevenue_Addition = dummyPax_Addition x dummyOWFare_Link

Case 2: more spilled local passengers than the number of empty seats
- dummyPax_Addition = Seats_Remain - (Seats_AC - Seats_AC x LFCF);
dummyRevenue_Addition = dummyPax_Addition x dummyOWFare_Link

End of PaxAllocationFile
(J = Index_Last(i))?

(Figure A.4: continued)
Update "PaxAllocationFile" using additional number of local passengers on board

\[ \text{Pax\_Onboard(dummyIndex\_Link)} = \text{Pax\_Onboard(dummyIndex\_Link)} + \text{dummyPax\_Addition} \]

Update FlightPaxTypeFile using additional number of local passengers on board and additional revenues generated

\[ \text{Pax\_Onboard\_Sum(i)} = \text{dummyPax\_Onboard\_Sum} + \text{dummyPax\_Addition} \]
\[ \text{Revenue\_Link(i)} = \text{dummyRevenue\_Link} + \text{dummyRevenue\_Addition} \]

End of FlightPaxTypeFile?

(Figure A.4: continued)
**Note 1 for Figure A.4:** Retrieved data fields of "FlightPaxTypeFile"

- FlightLinkld(i) = identification code of a flight leg
- Seats(i) = number of seats of an aircraft assigned to FlightLinkld(i)
- No_PaxType(i) = number of passenger type on FlightLinkld(i)
- Index_First(i) = first index number of passenger types associated with FlightLinkld(i)
- Index_Last(i) = last index number of passenger types associated with FlightLinkld(i)
- Pax_Allocated(i) = number of passenger demand allocated in a previous routing

*Sample file structure that provided input data to FlightPaxTypeFile:*

<table>
<thead>
<tr>
<th>Index</th>
<th>True_Org</th>
<th>True_Dest</th>
<th>Chain</th>
<th>Flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CMH</td>
<td>BOS</td>
<td>UA100</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>CMH</td>
<td>BOS</td>
<td>UA150-UA200</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>CMH</td>
<td>BOS</td>
<td>UA300-UA400</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>CMH</td>
<td>BOS</td>
<td>UA500</td>
<td></td>
</tr>
</tbody>
</table>

**Note 2 on Figure A.4:** Illustration of unbalanced number of passengers of the same passenger type across the flight chain

*After the 1st iteration process*

- **Flight #1**
  - (# of seats on AC = 130; # of pax. = 130)
  - L.F. = 100%
  - Spilled pax. = 0

- **Flight #2**
  - (# of seats on AC = 130; # of pax. = 130)
  - L.F. = 100%
  - Spilled pax. = 0

- **Flight #3**
  - (# of seats on AC = 110; # of pax. = 110)
  - L.F. = 100%
  - Spilled pax. = 0

*After the 2nd iteration process*

- **Flight #1**
  - (# of seats on AC = 130; # of pax. = 115)
  - L.F. = 88%
  - Spilled pax. = 15

- **Flight #2**
  - (# of seats on AC = 130; # of pax. = 130)
  - L.F. = 85%
  - Spilled pax. = 20

- **Flight #3**
  - (# of seats on AC = 110; # of pax. = 110)
  - L.F. = 100%
  - Spilled pax. = 0