Airline Scheduling: An Overview

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The flight schedule is the central element of an airline's planning process, aimed at optimizing the deployment of the airline's resources in order to meet demands and maximize profits. In this paper, we present an overview of contributions to airline scheduling made by operations research professionals during the past 20 years or so. The overview follows the development of airline scheduling methodology from an early emphasis on standard quantitative optimization techniques to the recent trends toward a structured planning process in which all parts of the airline participate in the "construction" and "evaluation" of schedules, combining exact mathematical programming algorithms and heuristics.

INTRODUCTION

In a commercial airline the flight schedule is a central element of the planning process. It defines not only the product but to a large extent also the production plan. Given a flight schedule, a significant portion of costs and revenues are fixed. Optimization of the flight schedule, therefore, is central to finding the most efficient and effective deployment of an airline's resources. By implication—if the market and regulatory mechanism works properly—it is also critical for obtaining an air transportation system which satisfies public objectives.

Recognizing the central nature of the schedule, OR professionals both within and outside of airlines have been working on the development of methods for obtaining optimal schedules since the 1950s. The work has been discussed extensively in the symposia and study group meetings of AGIFORS (Airline Group of the International Federation of Operational Research Societies), a kindred society of IFORS and at other professional

Transportation Science
Vol. 19, No. 2, May 1985

0041-1655/85/1902-0127 $01.25

society meetings. Some of the work has been published in the relatively inaccessible *Proceedings of AGIFORS*, but most of the work has only been documented in internal company reports, informal reports, or not documented at all.

Much of the early work was on models which can readily be formulated mathematically and solved by a standard optimization algorithm. In general terms, such a model may be formulated as follows.

Given:

1. A set of demand functions and associated revenues for every passenger origin-destination pair ("market") over the time-of-the-day and the day-of-the-week of the planning cycle;
2. Route characteristics—distances, times, and operating restrictions;
3. Aircraft characteristics and operating costs; and
4. Operational and managerial constraints.

Find:

A set of flights with associated assignments of aircraft and times of departure and arrival which maximize profits.

Mathematical programming was thought to be the method for obtaining optimal solutions. These modeling efforts were essentially an extension of the formulation by DANTZIG.[1]

However, it was soon recognized that in order to obtain meaningful schedules it was necessary to represent airline operations in considerable detail in the model. The problem of airline scheduling amounts to determining concurrent flows of passengers, cargo, aircraft, and flight crews through a space-time network and scheduling the aircraft maintenance or determining the deployment of many of an airline's ground based resources, such as airport gates. It is inseparable from the marketing plan. Representing all this detail led to ever-increasing complexity of the models and to prohibitively large numbers of variables. Although many closed-form endeavors were begun, none were ever completed, largely because computers at the time were not capable of handling the size and complexity of the models. The perception was, however, that eventually the size and efficiency of computers would be capable of solving some sort of closed-form model.

The consensus today is that the problem of aircraft scheduling is unsolvable by quantitative optimization techniques. For one, scheduling an airline virtually amounts to optimization of the whole airline operation: its effects extend into almost every department. For another, there are a number of objectives and constraints which are difficult to quantify.

It is therefore recognized that the airline scheduling problem is best solved through a structured planning process in which all parts of the airline participate. Much of the work may be handled by a computer, but many of the crucial decisions and choices are made by humans. Systems of this type emerged in the 1960s under the name of schedule development and evaluation systems (BROUGH,[2,3] TOBIN AND BUTFIELD,[4] LOUGHRAN,[5] ETSCHMAIER,[6] ELCE,[7] AGARD,[8] and WALKER-POWELL[9]). A central planning department develops a draft schedule which is evaluated by the various operating departments in terms of feasibility and economics. Based on these evaluations, a new draft schedule is prepared. The iterative process is continued until either covergence is reached or time has expired. The two phases of this iterative process are referred to as "schedule construction" and "schedule evaluation."

Most airlines today either explicitly or implicitly have a system of this kind in place. The systems are designed so that they can grow in an evolutionary process. Critical elements of the systems are

- A set of data bases
- A man-machine interactive environment
- Clear definition and allocation of responsibilities.

Quantitative models are used throughout these systems: for constructing the draft schedules and for evaluating them according to the criteria of the various operating departments.

SCHEDULE CONSTRUCTION

SCHEDULE CONSTRUCTION takes into consideration only factors of primary importance such as: the passengers as represented through some simplified demand function; the aircraft with their operating characteristics, including some simplified cost function; the geography of the route network; some simplified representation of authorization and commitment to serve routes; and in some cases, the expected behavior of the competition.

A description of models available at the time is contained in SIMPSON[10,11] and ETSCHMAIER.[12] A more up-to-date description is being prepared by the authors (ETSCHMAIER AND MATHAISEL[13]). Some references to schedule construction models are also contained in a survey of the entire scheduling field by BODIN et al.[14]

The approaches taken in the schedule construction process can be divided into direct approaches and into stepwise ones. The direct approaches use some heuristic procedure for preparing a schedule by sequentially selecting flights and possibly making small changes in flights previously selected. While some old models were entirely computer based (AGIN,[15,16] CHAN,[17] LARSON,[18,19] LEVIN,[20–22] BENBASSET,[23] SOUMIS,[24] SOUMIS et al.,[25] Loughran[5]), models currently in use provide a man-machine interactive environment in which the selection of flights is made by the planner (NIEDERER,[26] WILLIAMSON,[27] LUBOW,[28] ELIAS,[29] SMITH AND KYLE,[30] LIU,[31] DECKWITZ,[32] LABOVITZ AND JORGENSEN[33]).

Stepwise approaches begin by selecting routes which are to be served and determining the frequency of service on each route. This step is called Frequency Planning or Frequency Optimization (Dantzig,[1] KUSHIGE,[34] MILLER,[35–37] MATHAISEL,[38] MATHAISEL AND DE LAMOTTE,[39] HANDLER AND SIMPSON,[40] DE LAMOTTE AND MATHAISEL,[41] Elce,[7] JESSIMAN AND WARD,[42] ETSCHMAIER,[6,43,44] SWAN,[45,46] SOUDAROVICH,[47] ETSCHMAIER AND RICHARDSON,[48,49] RICHARDSON[50,51]). The second step determines departure times on the basis of the time-of-the-day variability of demand and of the possible connections of flights to other airlines (SIMPSON,[52] Jessiman and Ward,[42] STRUVE,[53] GAGNON[54]). In the third step, departure times are checked for operational feasibility. 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 (Loughran,[5] RICHTER,[55,56] Etschmaier,[12] TEWINKEL,[57] Struve,[53] Simpson,[11] MATHAISEL,[58] LABOMBARDA AND NICOLETTI[59]).

Which approach is best for solving the aircraft scheduling problem for a particular airline depends on the structural characteristics of the airline, most importantly the route structure (linear vs. hub-and-spoke networks) and the market structure (density, volume and elasticity of demand). For example, an airline that operates in a remote area without competition from surface transportation modes or from other airlines and with a demand relatively insensitive to the time of departure will find a stepwise approach very useful. On the other hand, an airline in a highly competitive market with a demand highly sensitive to time will obtain meaningless results from a stepwise approach and is best served by a direct approach.

SCHEDULE EVALUATION

THE PROCESS of schedule evaluation typically involves the whole airline. Since tactical decisions related to the implementation of the schedule are the responsibility of the various operating departments, each one of these operating departments is responsible for the evaluation of the draft schedule for the aspects of particular importance to it. The objective of these evaluations is:

(a) To estimate with some accuracy the costs that will be incurred and the revenues that will accrue from flying the proposed schedule; and
(b) To identify any features of the schedule which will be costly to

implement and for which, from the perspective of each department's operating responsibility, a change would be desirable.

The determination of the cost of operating a schedule for most departments involves the development of relatively detailed tactical plans. The following operational factors are usually considered explicitly:

1. A more precise demand function
2. Punctuality inherent in the schedule
3. Cockpit and cabin crews
4. Ground crews and ground facilities
5. Aircraft maintenance requirements.

Evaluation according to each factor requires a different type of model. For an extensive discussion of these models we refer to Etschmaier and Mathaisel.[13]

The evaluation of the schedule according to a more precise demand function essentially simulates the choices which passengers make in view of the flight schedules, competitor's flight schedules, differences in equipment and fares, and limited aircraft capacities. In view of the increased competitiveness of the airline industry, most of the more recent work that is actually applied by airlines is not in the public domain. Published models and discussions can be found in Gagnon,[54] GIRARD,[60] LOUGHRAN,[5] MATHAISEL,[61] WAN AND JOWETT,[62] POLLACK,[63] Elias,[29] BUHR et al.,[64] SHAW,[65,66] WALKER-POWELL,[67] TEONG,[68] and BARNARD.[69]

Evaluations of the schedule in terms of punctuality determines the stability of the schedule against disturbances. Because the execution of an airline schedule amounts to interdependent movements of aircraft, crews, passengers and cargo through a complex network in space and time, the situation is very complicated. Large simulation models are required to determine to what extent some disturbance of the schedule (e.g., through inclement weather, or through airspace congestion) propagates throughout the system. A discussion of possible approaches and of some model formulations is contained in ETSCHMAIER AND ROTHSTEIN.[70,71] Descriptions of specific models are contained in WILSON.[72]

Evaluation of the flight schedule in terms of cockpit and cabin crews is done by developing detailed crew schedules. The same models are used—possibly with simplifications—as are used for the preparation of the actual crew schedules. The subject of crew scheduling has received wide attention independent of schedule evaluation. Summaries of the work in crew scheduling are contained in ARABEYRE et al.,[73] Bodin et al.,[14] and BALL AND ROBERTS.[74]

Evaluation of the flight schedule in terms of ground crews and ground facilities requires relatively detailed planning of the assignments of crews and facilities. Examples for the types of problems that have to be solved are the assignment of gates to aircraft, and rostering for ground crews. Descriptions of work in the area are contained in MANGOUBI AND MATHAISEL.[75]

Evaluation of the flight schedule in terms of maintenance requirements determines whether all the maintenance requirements of aircraft can actually be met, given the sequences of flying and ground times prescribed by the schedule, and given the maintenance resources that are available. A discussion of the interdependence that exists between the flight schedule and maintenance is given in Etschmaier and Rothstein.[70,71] Models of relevance are described in KAYUKAWA,[76] BIRD,[77] and LEE AND RENO.[78]

Several airlines today have an extensive repertoire of heuristic procedures for schedule evaluation. Development of many of these models required few of the mathematical skills of OR specialists. Instead, it focused on the development and programming of user-friendly man-machine interactive procedures. We expect that future work will largely concentrate in this direction, with numerical displays replaced by color graphics whenever practical (Lubow,[28] SIMPSON AND MATHAISEL,[79] Deckwitz[32]). Also, there is room for the enhancement of many of the procedures currently in use.

CONCLUSIONS FROM PREVIOUS WORK

WHAT ALL the previous work in aircraft scheduling has demonstrated is the versatility of the human mind in planning decisions and the great contribution the human mind can make to developing complex statements like airline schedules. The human is best able to rapidly adapt to changing situations and grasp the meaning of unforeseen phenomena. Although technologies are available for quantifying qualitative phenomena, and computer models can perform a great deal of data reduction, manipulation, and presentation, and although artificial intelligence (expert systems) may play an ever-increasing role, in general only the human is able to assimilate these phenomena with any degree of efficiency. As a consequence, work on airline scheduling now seems to be concentrating on the development of a systematic interaction between man and computer. The computer, especially in the initial stages, is confined to handling the very tedious arithmetic chores involved in determining the feasibility of a schedule, while man's role is recognizing patterns and suggesting new solutions or alterations to existing solutions in the light of certain evaluations.

To date, the role of the computer has been rather limited and the full potential of the approach sketched above has not been realized. There are no systems in practical use which provide an optimal interface between man and computer, and there are few which employ imbedded operations research models for optimization and simulation. However, the contributions of operations research in this area should not be underestimated. These contributions lie mainly in the conceptualization and formulation of the scheduling process. This by no means simple or easy task involves definition of the steps through which the process evolves as well as of the desirable kind of interaction between man and computer. Significant work has been carried out in both areas.

DIRECTIONS FOR FUTURE WORK

MOST RECENTLY, a number of events has caused dramatic changes in the nature of airline operations. The most important of these are: The Airline Deregulation Act of 1978, the fuel crisis, the emergence of competition with specialized low-cost carriers and commuters, and the resulting abundance of promotional and discount fares in all major markets. The following summarizes the more important changes which these events have caused.

(a) Schedules can no longer be prepared a long time ahead of implementation because the environment is changing too rapidly and too unpredictably. At the time when the actual flight schedule is firmed up, most decisions about investments and resource deployment have been made and are irrevocable. The type of model which is now necessary to arrive at an "optimal" schedule is one that builds on all the available resources rather than on just the aircraft fleet.

(b) Through various forms of discount fares, it is possible to change the time preference and—to a lesser extent—even the destination of a sizeable part of the passenger demand. New forms of demand functions and an effective capacity/yield management system have to be devised. Although it can be argued that a schedule should be developed without considering discount traffic, it is easy to see that inclusion of potential discount traffic will make a significant difference.

(c) Competition is forcing airlines into different patterns of operation. Airlines are consolidating their operations into hub-and-spoke networks with the hubs providing an opportunity for flights to "feed" each other. None of the scheduling models which are currently available are capable of either determining which stations to best designate as hubs or—once the hubs have been determined—finding the best times for the "banks of flights." Clearly, there is a need for such models, but before they can be developed, a more thorough understanding of the dynamic nature of hubs is necessary.

(d) The relative importance of the various factors in the cost equation has been changed dramatically. On one hand, the price of fuel has increased several-fold and may vary significantly between stations. On the other hand, there are many depreciated aircraft around which—except for fuel efficiency—are identical in performance to other, nondepreciated aircraft. The consequence of both is that the maximal utilization of aircraft for many airlines no longer is a prime objective. Instead, it is desirable to find optimal ways of mixing aircraft of different capacities and efficiencies. This principle is not new but has been used in isolated systems for a long time, as in the Eastern Airlines shuttle service. The possibility of using inefficient equipment to cover peak loads or unforeseeable requirements could be included explicitly in future generations of scheduling models.

(e) The schedule becomes separated from longer range decisions. In the past, investment decisions such as the purchase of new aircraft have often been based on projected future flight schedules. In today's environment this is no longer meaningful. What is required instead is an aggregate representation of future service opportunities. Long range decisions can then more directly be made to include minimization of risk. Some initial work in this direction is reported in Mathaisel.[38] It is clear now that risk should have been considered more explicitly in investment decisions even in the earlier airline environment. The fleet procurement decisions by major carriers might have been different if risk had been considered.

Airline scheduling thus has entered a new phase. Many of the basic assumptions are being reevaluated. But all changes increase the importance of flexible, interactive planning systems with effective synergism between man and the computer.

ACKNOWLEDGMENTS

THE AUTHORS are indebted to Professors Robert Simpson and Amedeo Odoni of MIT for their generous comments and suggestions in writing this paper.

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