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Operations Management Perspectives in the Air Transport Management

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ARTICLE INFO

Article history

Received: 12 November 2018

Accepted: 24 December 2018

Published: 7 March 2019

Keywords:

Air transportation

Operations management

Runway scheduling

Fleet assignment

Crew scheduling

Aircraft routing

Demand forecasting

Gate assignment

ABSTRACT

The area of operations management has had a substantial effect on the today's air transportation management. Having moved with huge demand from management to obtain a competitive advantage in the market, the airlines are utilizing advanced optimization techniques to develop decision support systems for operations management and control. In order to provide a service with high quality and low cost, airlines spend a tremendous amount of resources and effort to generate profitable and cost-effective fare classes, flight schedules, fleet plans, aircraft routes, crew scheduling, gate assignment, etc. In this paper, the techniques and operations management applications that are used in the air transportation industry are reviewed including demand forecasting, fleet assignment, aircraft routing, crew scheduling, runway scheduling problem and gate assignment.

1. Introduction

Especially in recent years, the aviation industry has been growing steadily. This increase in the aviation sector, which was achieved by the first jet flight in 1949 reached 70 times nowadays; brought it with the following: the desire to reach opportunities in countries with developed living standards, with the creation of international aviation law, new markets to airline companies, increase in demand because it is a safe way of transportation, lower prices due to increased productivity and competitive environment^[1].

According to statistics published by the International

Civil Aviation Organization (ICAO) in 2006, there exists more than 900 commercial airline companies, 22,000 airline fleets, 1,670 airports with millions of kilometers of network, 2 billion passengers per year, 2.1 million employees (check-in officers, maintenance crew, etc.) and a very comprehensive accounting system which deals with the 40% of total import and export (ICAO 2006). Therefore, it is important to plan and manage this valuable system which has a very complex structure in terms of both airline companies and the General Directorate of State Airports Authority^[2].

The delay and complexity experienced at the airport has been one of the main problems of the aviation sector.

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If better planning was made only at 29 intensive airports in the United States (U.S.), a total savings of 400 aircraft could be achieved^[3]. After the security, the next most important issue for the US Department of Transportation, is managing the high passenger density^[4].

In order to provide all the constraints of the stakeholders (as presented in Figure 1), and to find an economical solution with high quality, airlines are spending a lot of resources and efforts in scheduling problems such as profitable and cost effective fare classes, flight schedules, fleet plans, routes, flight team plans, gate assignments, maintenance schedules, food service plans and baggage management. In addition to stakeholder-based constraints, there are some other factors such as; having already benefited from limited resources, there is not much room for movement and space to the changes, the environment in which the airline operates is a dynamic environment with ambiguities, adverse weather conditions, mechanical problems, malfunctions, fuel bottlenecks, illness of one flight crew, the plan made by the agents is very often interrupted and changed, flight team's working conditions, track availability, security etc. due to such factors as strict rules applied by the FAA (Federal Aviation Academy)^[5].

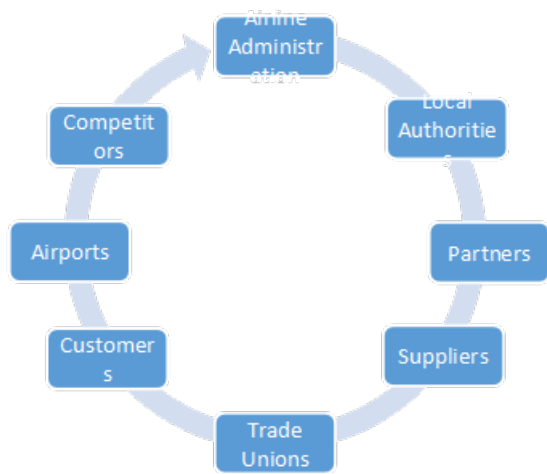


Figure 1. Aviation Industry Stakeholders

Three different departments are involved in airline companies; scheduling and network, operational planning and operation control departments^[6]. The scheduling and network department is responsible for the creation of feasible schedules at the planning stage. The aim of this unit is to increase the intentions such as market share, passenger income and to take measures to reduce the operational costs. In KLM Royal Dutch Airlines, this process takes approximately 2 months and the results are transferred to the operational plan department. The operational plan department makes minor changes on this chart taking into account the changes in the sector and the performance

of the operations in the airline industry. Approximately 2 weeks before the flight, it sends the results to the operation control department to make last-minute changes in different occasions.

'Delays' have been increasing in recent years due to the inability to show suitable charts or to adapt to the changes in the charts and to develop solutions that can respond to this change in a short time^[6]. According to a survey conducted by Eurocontrol in 2005, 42% of flights are delayed and almost half of these delays are 15 minutes or more. When the delays are examined in detail, it has been revealed that half of these delays are caused by airlines.

As a result, considering all the inputs mentioned above, it is important to establish a wide range of fleet decision making systems, including strategic planning such as route planning and airplane purchase for airlines, tactical level planning such as fuel planning, crew scheduling. It is very important to solve and analyze these problems with scientific methods.

In order to provide a service with high quality and low cost, airlines spend a tremendous amount of resources and effort to generate profitable and cost-effective fare classes, flight schedules, fleet plans, aircraft routes, crew scheduling, gate assignment, etc. In this paper, the techniques and operations management applications that are used in the air transportation industry are reviewed including demand forecasting, fleet assignment, aircraft routing, crew scheduling, runway scheduling problem and gate assignment.

2. Background

The implementation of airline planning and operations management consist of several activities and operations. The planning starts by strategic decisions which takes a long lead time, for instance, demand forecasting, (i.e, collecting the demand and supply). Then, a set of interrelated planning decisions are considered, for instance fleet assignment, aircraft routing, crew scheduling, are taken into account. The planning processes are generally completed by a month to a few months before the implementation of the schedule. Next, the operations phase is considered during the implementation of the planned schedule which takes into account flight and schedule recoveries. The Figure 2 reflects the main operations considered in the strategic, planning and operations phases of air transportation.

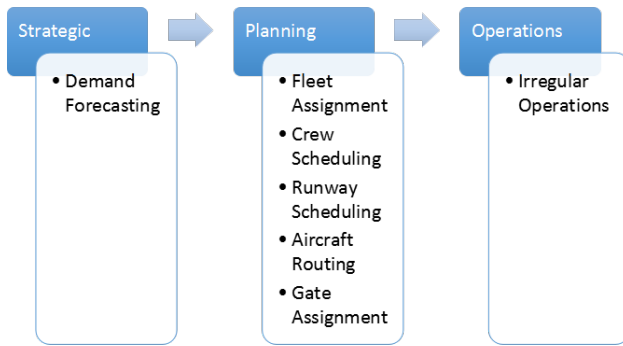


Figure 2. Processes in the strategic, planning and operations phases of the airlines

While the operations planning process may vary across airlines, it is complex in a sense that resource scheduling decisions are being made on demand forecasting, fleet assignment, crew scheduling, etc. A sample representation of a timeline is provided in Figure 3.

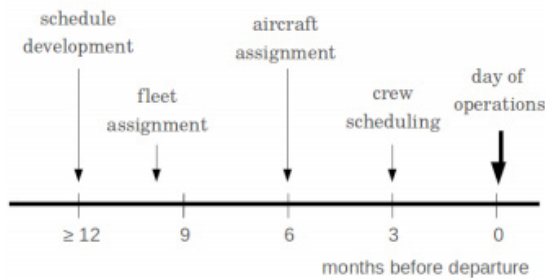


Figure 3. An Airline Planning Process [7]

The fundamental planning phase elements and their association in airline operations are illustrated in Figure 4. With regard to the proposed framework after the detailed literature review, the articles were reviewed into two major classes, namely aircraft operations in terminal manoeuvring area (TMA) and air traffic operations (ATO).

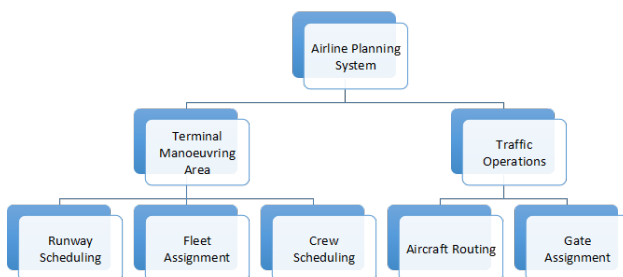


Figure 4. Framework of airline operations

In this paper, the operations research techniques and operations management applications that are used in the air transportation industry including demand forecasting,

fleet assignment, aircraft routing, crew scheduling, runway scheduling and gate assignment are reviewed.

2.1 Demand Forecasting

The purpose of the demand forecasting models, which are the stages of decision making in the long and middle term, is to predict the preferences of airline passengers for different alternatives of airports [8]. The main entry of this model is the demand estimation which is taking into account such factors as whether to travel or not, whether to use direct flights or connected flights if traveling, and which flight hub will be used if connected flights are used [9].

Making an accurate forecast is not only important for airlines and airports, but also for institutions such as the State Airports Authority in charge of that area. While airlines can make more profitable planning with a precise demand forecast, other agencies can also create better airport-related plans on these estimates [10]. For this reason, the creation of the correct models has an equal effect on stakeholders.

There are two different methods of overcoming the high passenger density in airlines [4]. The first is the expansion of the airports and the construction of an airport that will balance supply and demand. The second is to increase and to use the capacity more efficiently by utilizing methods such as pricing.

When the literature is examined, although the number of studies mostly based on questionnaires (such as [11]) seems to be high, the number of studies related to analyzing the preferences of passengers using airway transportation with discrete choice models has increased in recent years, and this complex process is modeled more realistically [10].

The factors affecting the decision of passengers who use air transport can be divided into three: characteristic of the route (price, time of departure and arrival, number of connections, waiting times, flight time, the type and size of the aircraft, the characteristics of the airline company), social-economic character of the travelers (income, age, gender, airline loyalty club membership), character of the journey (business or vacation, domestic or international, departure or arrival airport (location and time zone)) [2]. Generally, it seems that passengers prefer airline alternatives that are cheaper, have fewer connections, have a proper take-off time and landing time, and offered by outstanding airlines.

The passenger's income and sensitivity to ticket prices are inversely proportional. High-income passengers are less sensitive to ticket prices. The age and gender of the traveler also play an important role in the selection of alternatives. For example, ladies usually do not prefer alter-

native flights late at night, and an airport far from the city. It seems that airline loyalty members have opted for the flight of that airline in order to collect miles.

Finally, the character of the journey also influences this choice. Passengers traveling on business are generally less sensitive to price than passengers traveling on vacation. However, it has been observed that business travelers also consider the arrival time more often. Generally, it is seen that these types of passengers prefer alternatives that arrive at the end of the day and that have no connection.

When the studies in the literature are examined, studies which evaluate one or more of the factors in these 3 categories have been reached; however, no studies have been found to evaluate the whole of these factors^[8,9]. While a model was developed that takes into account factors such as ticket prices, frequency, flight times, direct flight, and time of departure^[9], service level is considered, whether it is a connected flight or not, airline company, ticket prices, type and capacity of the aircraft^[8].

2.2 Fleet Assignment

The Fleet Assignment Problem (FAP) deals with the assignment of each aircraft type to the specified flights on a chart according to the potential profitability, capacity and equipment that it has. FAP decisions have high impact on profitability, and are one of the most important parts of the scheduling problems of airline companies. Assigning an aircraft which has a small capacity may lead to improper demand management; on the other hand, assigning a large aircraft may cause unsold seats. FAP is considered to be a very difficult problem due to the large number of flights during the day and the close relationship of airline companies with other transactions^[12]. According to the research, the studies in the literature are divided into four, namely basic FAP models, FAP models integrated with other processes of the airline, FAP with additional coverage and dynamic FAP models.

2.2.1 Basic FAP Model

The constraints ensure that each flight is covered by a fleet type, the aircraft capacity is not exceeded, and the network balance^[13]. The basic FAP model was re-modeled based on Time Space Network^[14]. This model was later extended with the addition of constraints to consider the flight team^[15].

2.2.2 Integrated FAP Model

Although the FAP-related studies address FAP's independence from other airline planning and scheduling activities, it is closely related to activities such as departure/arrival times, departure/arrival airport, maintenance periods,

cycle planning and flight crew planning.

For example, a FAP solution that is not integrated with flight crew planning could result in the assignment of a cabin crew that does not have that type of aircraft certification. For this reason, it is necessary to develop models that can work together with these types of processes. Integrated fleet assignment and flight schedule models would provide a better solution than to deal with these problems separately. The first study on this subject was made by adding two constraints^[16]. Since one of the constraint is nonlinear and causes computational difficulty, the constraint can be used by performing the M transformation^[17].

In addition to integrated fleet assignment and flight schedule models, in the literature, fleet assignment has also been integrated with flight crew planning, maintenance scheduling and location problems, and most of these models have been achieved by adding a few constraints on the model proposed by^[13].

2.2.3 FAP with Additional Coverage

In addition to the studies described above, researchers have worked on removing assumptions such as the fixed costs used in the basic FAP, fixed demand and the planning on a daily basis. For example, weekly planning was worked on instead of daily planning^[18]. The integrated FAP was solved with crew pairing and routing problems, and provided heuristic methods^[19].

2.2.4 Dynamic FAP Model

Currently, airlines use flight schedules as an input to other activities, and they set their flight schedules 2-3 months before departure and assign their aircraft to the flight according to this schedule. However, due to uncertainty in demand, these appointments may need to be updated. For this reason, recently, researchers have been working on models that have been able to respond these changes dynamically, particularly in demand. A dynamic model has been developed that can both deal with the reassignment of fleet and re-timing in demand changes^[20]. This model has been solved by using L shape and multivariate adaptive regression splines cutting plane method by developing a model that can adapt dynamically to changing ambient conditions^[21]. The majority of the models in the literature are network-based models and their solutions range from a classical mathematical programming approach (integer programming, stochastic linear programming, etc.) to heuristic approaches^[22].

2.3 Crew Scheduling

Crew scheduling can be defined as the problem of assigning employees to jobs. In most sectors, the employees can

work instead of each other if needed, but in the aviation sector the problem can be considered more difficult than others because of the specialization of the workers for certain aircraft types^[23]. Although it differs from other sectoral problems, main problem is to reduce the labor cost and covering all work while obeying the contracts and safety rules. Because of that reason, this problem is very similar to other problems in many ways.

Crew scheduling differs in itself in terms of scheduling of pilots and cabin crew. Although the pilots and the cabin crew are generally evaluated together, it is more likely that the cabin crew will be able to fly with another aircraft compared to the pilots. Pilots only can fly with specific aircraft in the same 'fleet type'. For example, a pilot who can fly with an Airbus A320 most likely cannot fly with a Boeing 747.

Cost of crew for airlines is the highest cost after the fuel cost. American Airlines spent a total of \$ 1.3 billion for the crew in 1991, while Northwest Airlines spent \$ 1.05 billion in 1989 and United Airlines spent \$ 0.6 billion. So, planning and managing a resource of such high cost is very important^[24].

In the U.S., in one day, 2500 flights and 150 different cities are carried out with approximately 500 aircraft. Airlines need to provide both a cabin and a cockpit crew for each flight and that they need about 5000 cockpit and 10000 cabin members per month^[25].

When evaluated both in terms of cost and complexity, it is inevitable that the number of studies related to flight crew will increase in recent years. In early 1960s airlines was using schedules, which are formed manually. The first application of operations management methods to that problem began in 1969^[26].

Crew planning process is considered by the researchers as an optimization problem, and mathematical modeling of that problem is relatively easy compared to other problems. In this type of problem, the general approach is to develop an integer mathematical model with 0-1 variables. Often the study starts with planning pilots, and then the cabin team leader and the cabin crew respectively. Although the modeling phase starts with pilots due to their higher costs, the general structure of the problem is almost the same for all phases.

A different kind of classification for crew scheduling was also suggested^[27]. In this study, the crew scheduling problem is classified according to the geographical location of the airline. This study examines the European and American airlines in particular, showing that airlines in Europe have a fixed price policy instead of a pricing policy, which depends on the flight time and distance traveled. In Europe, most flights have to rotate (like getting up from

Istanbul and returning to Istanbul) so rather than solving the problem on a daily basis, airlines prefer longer periods. For example, Turkish Airlines, which is the biggest airline company in Turkey, solves the problem in monthly bases.

Another classification method for the problem is time-lapse. crew scheduling problem can be divided into 3 classes according to time-lapse, including daily, weekly and a specific period^[25]. Daily: It is assumed that all flights are made every day of the week on daily schedule. This type of planning is mostly used by US airlines, and flights in countries across Europe are more irregular. Most of the problems in the literature are concerned with daily planning. Weekly: The assumption in this type of planning is that the chart repeats weekly. Making the necessary changes for the irregular days mostly solves the problem. However, this approach cannot lead to optimal solutions mainly because there are too many irregular flights in European countries. Long Term: In this approach, crew is planned on a monthly basis. It is usually obtained by making minor changes in weekly planning. However, if weekly planning from daily plans is not optimal, these monthly plans may not be optimal for the same reason. In particular; irregular holidays, changes in flight times etc. prevent use of weekly plans in the long-term.

One of the earliest mathematical models for crew scheduling was created^[28]. The model create work schedule for each employee, taking into account the needs and pre-assignments. In order to create a feasible solution, it is necessary to select a solution in which a sufficient number of crew are assigned to a job and at least a member is assigned at each job.

A model was developed to facilitate the solution especially for large problems^[29]. In his study, he divided the crew into high-rank and low-rank members, and tried to satisfy the feasible solution by guaranteeing that airlines have enough crew for the days, which is called as bottleneck at first sight. This study proposes a solution algorithm to that model, and it shows that the developed method can provide better solutions especially for large scale problems when compared to standard algorithms used by a medium sized European airline in Europe.

Another classification can be made in terms of scope. Some studies in the literature have only approached the issue of crew scheduling, while others have dealt with the issue more extensively by including flight crew rostering. Some studies in the literature are about the trade-off between the robustness of the solution and the cost.

Robustness was emphasized by considering the integration of routing and crew scheduling^[30]. He runs the produced delayed scenarios in a deterministic model and

compares the results with the results of the statistical model he has developed. The nonlinear constraints arising in the model are solved by separating the problem function into the linear problems.

2.4 Runway Scheduling

Capacity expansion at airports, be it concerning the apron, airstrip, cargo, or terminal areas, is rooted in strategic decisions that require massive investments and long construction lead times. To achieve a most efficient use of such scarce resources, it is imperative to develop judicious planning strategies. Despite recent efforts and studies in the arena of aircraft operations, flight delays resulting in multi-billion-dollar losses are observed annually worldwide. Hence, there exists a pressing and persistent need to identify air traffic policies that can alleviate such frequent and costly inefficiencies. Airport terminal areas constitute a critical bottleneck resource that attracts a great deal of attention from decision-makers at airports worldwide.

Official flight delay statistics published by the U.S. Department of Transportation and Eurocontrol (The European Organization for the Safety of Air Navigation) are very alarming. Although such assessments may not be readily available for major airports in the Middle East, frequent and expensive flight delays pose a significant planning challenge for decision-makers worldwide.

Three primary types of operations take place in the terminal management areas: airway operations dealing with air traffic control inside the terminal area; runway operations pertaining to aircraft arrivals and departures that compete for a set of runways, which constitute a critically scarce resource; and finally taxiway operations related to aircraft operations from the runway to assigned gates, or vice versa. In this process, runways constitute the scarcest resource whose management greatly impacts the entire TMA performance^[31]. The runway assignment depends on the airport configuration (single runway, parallel or intersecting runways or combination of these), the direction of arriving aircraft, and departure route of the aircraft^[32]. The runway capacity is the maximum rate of aircraft arrivals or departures that can be accommodated by a single or multiple runways. The elements that affect the runway capacity are aircraft type, runway operation type (segregated or mixed), runway occupancy time, availability of taxiways, and weather conditions^[33]. The mixed-integer 0-1 programming formulation of the problem was provided in^[34] involving multiple runways with both immediate and general precedence decision variables.

2.4.1 Importance of Sequencing Decisions

The tactical problem of carefully assigning aircraft to

runways is often neglected, as efforts tend to focus on the intensive task of properly sequencing and separating aircraft that compete for the same runway. This tactical planning step constitutes an important feature of the integrated models, and is particularly relevant to airports that presently operate multiple runways as well as airports that are strategically considering the construction of additional runways to better accommodate sharply increasing air traffic volumes.

The so-called aircraft sequencing problem (ASP) aims at jointly optimizing the assignment of aircraft to runways and the concurrent sequencing of aircraft departures and arrivals on each runway at an airport. This scheduling effort is governed by two major requirements: minimum separation times between consecutive (as well as certain non-consecutive) operations and specified time-windows during which operations need to take place. Minimum separation times between operations are enforced to preclude the dangers of wake-vortex effects and to control the airspace congestion. The length of such safety buffers intimately depends on the aircraft operations (being departures or arrivals), the weight-class of the aircraft under consideration (small, large or heavy), and sequencing decisions. Considering a pair of consecutive operations, if the leading aircraft is heavy and the following aircraft is small, say, then a relatively large separation time is required for wake-vortex hazards to fully dissipate. Hence, the magnitudes of the separation times that must be enforced depend on the sequence of operations determined by air traffic controllers, which ultimately impacts the throughput of a runway. Sequencing decisions are, therefore, of critical importance, and latent inefficiencies and delays are imputable, in part, to high and possibly inequitable workloads, the intensive task of enforcing safety separation times, and the prevalent use of rudimentary sequencing rules. In addition to minimum separation times, arrivals and departures are required to take place within specified distinct time-windows that are determined using nominal schedules, which indicate the earliest time by when an aircraft could access the runway in an uninterrupted situation, and the maximum tolerable delay for this aircraft. A recent survey was provided on ASP where a comprehensive review of operations research techniques^[35].

The management of assigned airline time-slots is also receiving increasing attention in the literature. For instance, the value of runway time-slots for airline carriers has been investigated^[36] using a network flow model for flight rescheduling, whereas integration of a slot exchange mechanism was elaborated within a collaborative decision-making framework for airspace planning^[37, 38]. Despite the rich literature at hand, aircraft sequencing prob-

lems are often investigated under restrictive assumptions and idealized conditions.

Early works on aircraft arrival/departure sequencing date back to the late 70s^[39, 40]. Most studies reported in the literature focus on either departure or arrival operations^[41-47], often under the assumption of a single runway (or closely-spaced runways that are nonetheless interpreted as a single runway). A single machine scheduling problem was investigated where, for computational convenience, it is assumed that groups of identical jobs are sequenced with the objective of minimizing the total processing cost^[48]. A dynamic programming approach was developed for his single machine scheduling problem, and was applied in the context of sequencing arrival aircraft operations. An integer programming was used to sequence arriving aircraft inside the TMA^[49, 50]. The authors presented a formulation that takes into account the dynamic nature of the problem whereby every aircraft entering the TMA has a Nominal Landing Time (NLT) that depends on the present characteristics of the TMA, and the aircraft speed, among other features. The resulting combinatorial optimization problem was noted to be NP-hard, and in the case of zero ready-times, was shown to reduce to an Asymmetric Travelling Salesman Problem (ATSP). The Constrained Position Shifting (CPS) was proposed method to retain fairness among aircraft operators and increase the predictability of landing times^[51]. They present dynamic programming algorithms for runway scheduling under CPS.

2.4.2 Single Runway Problems and Asymmetric Traveling Salesman Problem Structure

The development of computationally tractable models for single runway problems is a founding stone for gaining modeling and computational insights into the more elaborate optimization problems. To this end, The aircraft sequencing problem (ASP) was modeled over a single runway as an asymmetric traveling salesman problem with the time-windows (ATSP-TW), where the objective is to minimize the greatest (last) aircraft's completion time^[52]. This basic ASP model includes ready-time and due-time restrictions for each aircraft operation, minimum safety separation times, and subtour elimination constraints.

It is important to recognize and exploit the ATSP-TW structure that characterizes operations over a single runway in order to perform a polyhedral analysis for multiple-runway aircraft sequencing problems. By taking advantage of the special structures of the problem, classes of valid inequalities can be derived in order to strengthen the continuous relaxation of the proposed models. The derivation of tighter relaxations can drastically improve problem solvability by enhancing the pruning effect of branch-and-

bound/cut algorithms that are commonly implemented in standard optimization solvers such as CPLEX. The usefulness of this concept has been demonstrated for several ATSP-related problems. For instance, enhanced formulations for the ATSP employing Miller-Tucker-Zemlin subtour elimination constraints, with and without precedence structures^[53-55]. Also, an alternative new polynomial length formulation of this problem is proposed^[56]. Further tightened polynomial length formulations using RLT-based lifting, and path-based and flow-based constraints have been developed^[12], and extensions to multiple traveling salesman with application to the steel industry are addressed.

2.4.3 Slot-exchange Mechanism in Airspace Planning

The aircraft sequencing models under stochastic time-windows and weather-based disruptions capitalize on elements of the Airspace Planning and Collaborative Decision-Making Model (APCDM) developed^[57, 58]. This is a large-scale mixed-integer programming model for improving the management of the US national airspace where under the scenario of a severe convective weather system, an optimal set of flight trajectories is selected amongst a set of alternative flight plans for the affected flights, while complying with sector workload, aviation safety rules, and airline carrier equity constraints. This framework has been recently extended^[37] in order to incorporate a slot-exchange mechanism amongst airline carriers that is regulated by the collaborative decision-making process between the Federal Aviation Administration (FAA) and airline companies. Specifically, individual airline carriers are assigned sets of operating time-slots by the FAA, but can barter these slots subject to specified trade offer restrictions with the FAA acting as the mediator.

2.4.4 Solution Methodologies

The aircraft sequencing problem over a single runway (modeled as ATSP-TW) is an NP-hard combinatorial optimization problem. As a consequence, the generalized and extended aircraft sequencing problems belong to a class of particularly challenging optimization problems. Exact solution methods (typically based on branch-and-bound algorithms) are practical only for small to moderately-sized problem instances. Solving larger instances to near optimality in reasonable computational times requires the design of specialized heuristics that are rooted in mathematical programming approaches, constructive search strategies, and metaheuristic paradigms, or hybrid approaches where both frameworks are synergistically employed. The proposed solution methodologies involve the

following components:

2.4.4.1 Fast Preprocessing/Probing Procedures

Such procedures aim at a priori fixing the value of certain binary sequencing variables, thereby determining the relative order of certain aircrafts without loss of optimality. This requires a judicious analysis of input parameter values and the ability to infer partial sequenced that must belong to an optimal schedule by means of logical implications. Such pre-processing routines and inference rules significantly reduce the problem size and complexity, contribute to strengthening the underlying relaxation of the model, and speed up its solution.

2.4.4.2 Polyhedral Analyses

Thorough polyhedral analyses are conducted to enhance the solvability of the different proposed mixed-integer 0-1 programs by strengthening their underlying continuous relaxations. To this end, computationally effective classes of valid inequalities are developed based on the special multiple asymmetric traveling salesman problem structure within the proposed formulations^[59]. Modern lifting procedures based on the Reformulation-Linearization Technique is also explored to strengthen the models, and to derive tight partial convex hull representations, especially in the vicinity of optimal solutions^[53-55].

2.4.4.3 Decomposition Approaches

The class of multiple-runway aircraft sequencing problem without pre-assignment of aircraft to runways exhibits a special structure that lends itself to decomposition approached^[59,60]. The associated mixed-integer programs involve coupling constraints that reflect dependencies across runways along with multiple independent sets of constraints pertaining to sequencing operations related to individual runways.

2.4.4.4 Column Generation Approaches

Column generation approaches^[61,62] offer a practical solution framework to obtain optimal solutions to the set partitioning formulations^[52] such as those arising in the context of the joint aircraft assignment-sequencing problem over multiple runways. Such approaches orchestrate a so-called restricted master program and a subproblem in order to dynamically generate and adjoin attractive patterns to the restricted master program. A key ingredient to the column generation approach that will be developed for these set partitioning formulations in to suitably coordinate the patterns generated so that minimum separation time constraints for departures across runways are satisfied when patterns are generated. To this end, innovative

extensions to the column generation algorithmic features described ensure a proper coordination of patterns^[52, 63].

2.4.4.5 Metaheuristics

Metaheuristics such as Genetic Algorithm (GA), Simulated Annealing (SA), Tabu Search (TS), and Ant Colony Optimization (ACO), among others, have shown to be robust methods for solving optimization problems. The literature abounds with studies where metaheuristics are implemented to solve difficult combinatorial optimization problems in deterministic and stochastic setting (see^[64] for an extensive survey of metaheuristic search paradigms;^[65] for a survey of metaheuristic approaches for deterministic combinatorial optimization with applications to scheduling and routing;^[66] for a recent survey of metaheuristic approaches for stochastic combinatorial optimization).

As far as aircraft sequencing problems are concerned, practical applications are to be found in^[46] where a GA is presented to schedule aircraft arrivals at London Heathrow airport, whereas^[43] proposed a TS algorithm for aircraft departures at that same airport. The multiple runway static Aircraft Landing Problem was studied where the set of aircraft that are waiting to land is known^[67]. They presented two population-based metaheuristics (Scatter Search and Binomic Algorithm), and the computational results to problem instances with up to 500 aircrafts and five runways indicate that good quality solutions are attainable in manageable times. Others work employed Gas for this problem and reported good quality solutions^[68, 69]. In another related work, the single runway arrival problem was solved in which an arrival schedule must be determined taking airlines cost into account^[70]. Their prescribed local search heuristic solved problem instances with over 100 flights within a few minutes, and large cost savings for the airlines were achieved using the proposed approach over a realistic schedule. Recently, the ASP over multiple runways was studied, under mixed mode operations with the objective of minimizing the total weighted tardiness of aircraft landings and departures simultaneously. The greedy algorithms, namely the Adapted Apparent Tardiness Cost with Separation and Ready Times (AATCSR), the Earliest Ready Time (ERT) and the Fast Priority Index (FPI) are proposed. To improve the results obtained from the greedy algorithms, they integrated with Metaheuristics for Randomized Priority Search (Meta-RaPS) applied and Simulated Annealing algorithms^[71].

2.5 Aircraft Routing

In the fleet assignment problem mentioned in the previous section, aircraft types were assigned to flights. For example; the flight from Ankara to Istanbul on November

30, 2017 at 14:05 will be carried out with a Boeing 737 aircraft. However, as it can be seen from that example, it is not yet known exactly which specific aircraft was assigned to this flight. Normally, the desired situation is to determine which aircraft is assigned to this flight based on the tail number. For this reason, additional operations are needed.

This process is known as aircraft routing in the literature, and the aim is to determine which aircraft will fly on a particular route. It takes 4-7 days to return from the origin to the same place again, and the aircraft is also subjected to some activities such as maintenance at this time^[2]. When the studies in the literature are examined, it can be seen that studies are generally divided into different classes with respect to the assumptions of such activities.

The Federal Aviation Authority (FAA) mandates airlines to care in many different types and periods. These maintenances are called A, B, C and D and the maintenance intervals are different from each other. Class A maintenance, is often considered in the problem of aircraft routing, where only the main systems (engine, landing gear, etc.) are visually inspected and simple operations are performed. This maintenance is usually done after a total of 65 hours of flight, and airline companies often solve this problem by treating it as a routing problem.

A problem of routing for American Airlines was worked on taking maintenance activities into consideration^[72]. Just as in the previous studies, appropriate roots for aircraft were mathematically modelled to take into account maintenance constraints^[73]. Dynamic effects of unexpected weather conditions on the route was studied and suggested a dynamic re-routing with a stochastic integer-programming model^[74].

In literature, there are some other methods, which can be classified in terms of their scope. For example, while some studies only deal with the problem of routing, some have addressed both the routing and the crew pairing problem to be explained in the next section. In this kind of models, which have increased in numbers in recent years, the aim is only sub optimal because the result obtained by solving the routing problem actually examined the problem from the airway perspective.

For example, it tried to find the lowest cost by considering both the problem of routing and crew scheduling^[75]. The same problem was studied by integrating the 'flight retiming' problem to that model^[76]. In^[77], models and solution methods that deal with both fleet assignment and the routing problem were studied. The purpose of that study is to assign the aircraft to a minimum cost flight on the basis of both the aircraft type and the tail number, to satisfy the constraints of maintenance and other activities

on the flight schedule. The most comprehensive work on this subject was made^[78]. In this work, the problem is addressed in a wide variety of ways, including the flight schedules, fleet assignment and flexible retiming.

2.6 Gate Assignment

The problem of gate assignment can be defined as the problem of matching the gates is connecting the aircraft and the terminal area^[2]. Each aircraft should be assigned to only one gate. If there are not enough gates, the airplanes are parked at the apron and the passengers are transported to the terminal by service vehicles. In particular, being close to next flight of reserved gate for passengers who have connecting flights will affect the walking distances and baggage transfers.

The Gate Assignment Problem (GAP) can have many goals. The common goals used in the GAP are as follows: the number of unassigned aircraft should be minimized, proper gate assignment for some aircraft types should be maximized, walking distance for passengers should be minimized, the differences between the current schedule and the reference schedule are minimized (robust), reduce the number of expensive aircraft towing procedures^[79]. A good schedule must provide the following constraints: a gate can serve only one aircraft at the same time, service and space requirements of airplanes (in some cases, depending on the size of the aircraft in the neighbouring gates, the airplane cannot be assigned to the gate due to lack of space), minimum time of stay and minimum time between two consecutive aircraft should be guaranteed.

The GAP was accepted as a non-deterministic problem due to delays and cancellations in the flights^[2]. A delay on the departing flight means that the aircraft has been occupied by that aircraft for a longer period of time, so that the incoming flight is reserved for another gate or waiting at the apron, and the delay on the incoming flight means that additional time is available for the aircraft at that gate.

Basic inputs of GAP; departure and landing times, aircraft type, number of passengers in the air, cargo volume, domestic/international flight, gate preferences and ground services needed^[79]. In addition, as mentioned in the problem of routing, aircraft have to carry out class A maintenance that corresponds to their arrival points. For this reason, the assigned gate may need to be suitable for this maintenance.

When the GAP is taken into consideration, models can be assessed according to the time period and objective function. Models with single or multiple time periods: In a single time period mode, a single plane can be assigned to each gate, while multiple time periods can be assigned to more than one aircraft because the time is available in

models with multiple time periods. Here the time span should be well chosen because it affects the size of the problem and the rates of gate usage highly.

The GAP with single time period; a facility can be modeled by drawing an analogy from the quadratic assignment problem, which is a location selection problem. The cost of assigning an gate depends on the placement of the other gates and the passenger volume between these gates^[79].

Type of objective function: Reduction of walking distance is one of the most used objective. Besides this purpose, there may be different purposes with passenger base and airport base. In addition to walking distance, the distance of the baggage carriage was also considered^[79]. In addition to these, the objectives related to aircraft withdrawal procedures and gate preferences are also confronted as airport specific objectives. One of first works on this subject was made in 1977^[80]. The cost function due to number of passengers, the distance between gate-gate, gate-check, gate-aircraft are tried to be minimized.

Intuitive and precise solutions were developed to show that the problem is the second-order assignment problem and NP-Hard^[81]. The problem was modelled as a 0-1 integer programming model and found the optimal solution by branch and nerve algorithm^[82]. However, the ongoing passengers in this study were not considered. This problem was solved using LP relaxation and an intuitive model by eliminating this missing model^[83]. Time compliance and robustness are also considered in the literature. In^[84], he determined to comply with time as a goal function. A procedure was developed for a robust GAP in his work^[85].

Since GAP is an NP-hard problem, researchers have recently used particularly simulated and intuitive approaches. While a simulation-based model was modelled^[86], a heuristic method was developed in which flights were assigned to the same gate without collision^[87]. The number of special gates for airlines is increasing. However, these studies are insufficient. One of the most recent works on the use of special gates was made^[88].

3. Discussion

When the models in the literature are examined from the viewpoint of technical complexity, it is seen that the models have not a complicated structure but when evaluated in terms of solution methods, especially intuitive and meta-analytical methods are more preferred than exact solutions in recent times.

When the uncertainty level is considered to be established in order to make a decision in a wide range from the strategic level to the tactical level in terms of uncer-

tainty level and when it is evaluated from the standpoint of stakeholders, it is considered that the results have a pluralistic structure because they will be used by institutions such as airlines, airport officials and State Airports Authorities. It said. The fact that uncertainty is particularly important in terms of the cost and hence the future of the company, compared to tactical level decisions, especially on strategic level decisions, makes strategic level decisions more quantitative. However, this type of work has not been achieved in the literature.

It can be said that the industry has a very gray structure in terms of values and disagreements. In Figure 1, it is necessary for airline companies to consider the aviation principles of the countries in which the airplane first travels and then travels or plans for long-term planning so that the system can follow the system regularly in terms of stakeholders. According to the characteristics of the airports that these companies will land / depart at the same time, traffic, runway number and number of lanes, gates and baggage operations^[2]. It is also necessary to consider the points. Another issue to be taken into consideration is the customer's flight schedules, pricing policies, etc. preferences. In most cases, airlines can partner with other airlines to increase the number of flight points and fly to longer distances. In this case, which airline will be partnered with, which resources will be shared, and so on. special issues are emerging.

One of the most striking among stakeholders is suppliers. Airlines, aircraft, fuel, aircraft parts, personnel, food, etc. Inputs are supplied by suppliers. The availability of these at the desired time and place is highly critical in terms of planning and therefore coordination with suppliers is required. In order to avoid strikes, the salaries, working conditions, etc. of the unions to which the employees are affiliated, entries in the fields should also be taken into account by the airlines. In the event of any disagreement, trade unions that can implement business sanctions and slowing down the business can very seriously affect the plans of the airlines. Finally, it is important that the competitors are continuously monitored in terms of capacity, price information, landing and departure times. One of the competing companies in the airline industry is a pioneer and plays an active role in the decisions of other companies.

4. Conclusions

Airlines and airports have been utilizing operations management techniques for almost 70 years. Operations management models and operations research techniques have had a remarkable effect on planning and managing oper-

ations within the airlines and airports. The developments in computer technology and optimization models have supported them to handle more complicated problems and provide solutions in a much shorter amount of time. This paper explores a variety of optimization models adopted by the airlines for scheduling and planning. Specifically, in this study, the techniques and operations management applications that are used in the air transportation industry including demand forecasting, fleet assignment, aircraft routing, crew scheduling, runway scheduling and gate assignment are reviewed.

References

- [1] Coldren GM, Koppelman FS, Kasturirangan K, Mukherjee A. Modeling aggregate air-travel itinerary shares: logit model development at a major US airline. *Journal of Air Transport Management*. 2003;9:361-9.
- [2] Abdelghany A, Abdelghany K. *Modeling applications in the airline industry*: Routledge; 2016.
- [3] De Neufville R. Airports of the future: the development of airport systems. *AIAA International Air and Space Symposium and Exposition: The Next 100 Years*2003. p. 2536.
- [4] Xiao Y, Fu X, Zhang A. Demand uncertainty and airport capacity choice. *Transportation Research Part B: Methodological*. 2013;57:91-104.
- [5] Yu G. *Operations Research in the Airline Industry*. International Series in Operations Research & Management Science. Kluwer Academic Publishers; 1998.
- [6] Burke EK, De Causmaecker P, De Maere G, Mulder J, Paelinck M, Berghe GV. A multi-objective approach for robust airline scheduling. *Computers & Operations Research*. 2010;37:822-32.
- [7] Petersen JD. Large-scale mixed integer optimization approaches for scheduling airline operations under irregularity: Georgia Institute of Technology; 2012.
- [8] Coldren GM, Koppelman FS. Modeling the competition among air-travel itinerary shares: GEV model development. *Transportation Research Part A: Policy and Practice*. 2005;39:345-65.
- [9] Hsiao C-Y, Hansen M. A passenger demand model for air transportation in a hub-and-spoke network. *Transportation Research Part E: Logistics and Transportation Review*. 2011;47:1112-25.
- [10] Hess S. Posterior analysis of random taste coefficients in air travel behaviour modelling. *Journal of Air Transport Management*. 2007;13:203-12.
- [11] Nassiri H, Rezaei A. Air itinerary choice in a low-frequency market: A decision rule approach. *Journal of Air Transport Management*. 2012;18:34-7.
- [12] Sherali HD, Bish EK, Zhu X. Airline fleet assignment concepts, models, and algorithms. *European Journal of Operational Research*. 2006;172:1-30.
- [13] Abara J. Applying integer linear programming to the fleet assignment problem. *Interfaces*. 1989;19:20-8.
- [14] Berge ME, Hopperstad CA. Demand driven dispatch: A method for dynamic aircraft capacity assignment, models and algorithms. *Operations Research*. 1993;41:153-68.
- [15] Rushmeier RA, Kontogiorgis SA. Advances in the optimization of airline fleet assignment. *Transportation Science*. 1997;31:159-69.
- [16] Desaulniers G, Desrosiers J, Dumas Y, Solomon MM, Soumis F. Daily aircraft routing and scheduling. *Management Science*. 1997;43:841-55.
- [17] Kohl N, Madsen OB. An optimization algorithm for the vehicle routing problem with time windows based on Lagrangian relaxation. *Operations Research*. 1997;45:395-406.
- [18] Belanger N, Desaulniers G, Soumis F, Desrosiers J. Periodic airline fleet assignment with time windows, spacing constraints, and time dependent revenues. *European Journal of Operational Research*. 2006;175:1754-66.
- [19] Salazar-González J-J. Approaches to solve the fleet-assignment, aircraft-routing, crew-pairing and crew-rostering problems of a regional carrier. *Omega*. 2014;43:71-82.
- [20] Jiang H, Barnhart C. Robust airline schedule design in a dynamic scheduling environment. *Computers & Operations Research*. 2013;40:831-40.
- [21] Pilla VL, Rosenberger JM, Chen V, Engsuwan N, Siddappa S. A multivariate adaptive regression splines cutting plane approach for solving a two-stage stochastic programming fleet assignment model. *European Journal of Operational Research*. 2012;216:162-71.
- [22] Bielli M, Bielli A, Rossi R. Trends in models and algorithms for fleet management. *Procedia-Social and Behavioral Sciences*. 2011;20:4-18.
- [23] Barnhart C, Cohn AM, Johnson EL, Klabjan D, Nemhauser GL, Vance PH. Airline crew scheduling. *Handbook of transportation science*: Springer; 2003. p. 517-60.
- [24] Anbil R, Gelman E, Patty B, Tanga R. Recent advances in crew-pairing optimization at American Airlines. *Interfaces*. 1991;21:62-74.
- [25] Gopalakrishnan B, Johnson EL. Airline crew scheduling: state-of-the-art. *Annals of Operations Research*. 2005;140:305-37.
- [26] Arabeyre J, Fearnley J, Steiger F, Teather W. The airline crew scheduling problem: A survey. *Transportation Science*. 1997;31:159-69.

- tation Science. 1969;3:140-63.
- [27] Andersson E, Housos E, Kohl N, Wedelin D. Crew pairing optimization. *Operations research in the airline industry*: Springer; 1998. p. 228-58.
- [28] Ryan DM. The solution of massive generalized set partitioning problems in aircrew rostering. *Journal of the operational research society*. 1992;43:459-67.
- [29] Dawid H, König J, Strauss C. An enhanced rostering model for airline crews. *Computers & Operations Research*. 2001;28:671-88.
- [30] Weide O, Ryan D, Ehr Gott M. An iterative approach to robust and integrated aircraft routing and crew scheduling. *Computers & Operations Research*. 2010;37:833-44.
- [31] Sherali HD, Hobeika AG, Trani AA, Kim BJ. An integrated simulation and dynamic programming approach for determining optimal runway exit locations. *Management Science*. 1992;38:1049-62.
- [32] Brinton CR. An implicit enumeration algorithm for arrival aircraft. *Digital Avionics Systems Conference, 1992 Proceedings, IEEE/AIAA 11th*: IEEE; 1992. p. 268-74.
- [33] Bazargan M, Fleming K, Subramanian P. A simulation study to investigate runway capacity using TAAM. *Simulation Conference, 2002 Proceedings of the Winter*: IEEE; 2002. p. 1235-43.
- [34] Al-Salem A, Farhadi F, Kharbeche M, Ghoniem A. Multiple-runway aircraft sequencing problems using mixed-integer programming. *IIE Annual Conference Proceedings: Institute of Industrial and Systems Engineers (IISE)*; 2012. p. 1.
- [35] Bennell JA, Mesgarpour M, Potts CN. Airport runway scheduling. *4OR*. 2011;9:115.
- [36] Cao J-M, Kanafani A. The value of runway time slots for airlines. *European Journal of Operational Research*. 2000;126:491-500.
- [37] Sherali HD, Hill JM, McCrea MV, Trani AA. Integrating slot exchange, safety, capacity, and equity mechanisms within an airspace flow program. *Transportation Science*. 2011;45:271-84.
- [38] Vossen T, Ball M. Optimization and mediated bartering models for ground delay programs. *Naval Research Logistics (NRL)*. 2006;53:75-90.
- [39] Dear RG, Sherif YS. The dynamic scheduling of aircraft in high density terminal areas. *Microelectronics Reliability*. 1989;29:743-9.
- [40] Dear RG, Sherif YS. An algorithm for computer assisted sequencing and scheduling of terminal area operations. *Transportation Research Part A: General*. 1991;25:129-39.
- [41] Artiouchine K, Baptiste P, Dürr C. Runway sequencing with holding patterns. *European Journal of Operational Research*. 2004.
- [42] Atkin JA, Burke EK, Greenwood JS. TSAT allocation at London Heathrow: the relationship between slot compliance, throughput and equity. *Public Transport*. 2010;2:173-98.
- [43] Atkin JA, Burke EK, Greenwood JS, Reeson D. Hybrid metaheuristics to aid runway scheduling at London Heathrow airport. *Transportation Science*. 2007;41:90-106.
- [44] Atkin JA, Burke EK, Greenwood JS, Reeson D. A metaheuristic approach to aircraft departure scheduling at London Heathrow airport. *Computer-aided Systems in Public Transport*: Springer; 2008. p. 235-52.
- [45] Beasley JE, Krishnamoorthy M, Sharaiha YM, Abramson D. Displacement problem and dynamically scheduling aircraft landings. *Journal of the operational research society*. 2004;55:54-64.
- [46] Beasley JE, Sonander J, Havelock P. Scheduling aircraft landings at London Heathrow using a population heuristic. *Journal of the operational research society*. 2001;52:483-93.
- [47] Venkatakrishnan C, Barnett A, Odoni AR. Landings at Logan Airport: Describing and increasing airport capacity. *Transportation Science*. 1993;27:211-27.
- [48] Psaraftis HN. A dynamic programming approach for sequencing groups of identical jobs. *Operations Research*. 1980;28:1347-59.
- [49] Bianco L, Dell'Olmo P, Giordani S. Scheduling models and algorithms for TMA traffic management. *Modelling and simulation in air traffic management*: Springer; 1997. p. 139-67.
- [50] Bianco L, Rinaldi G, Sassano A. A combinatorial optimization approach to aircraft sequencing problem. *Flow Control of Congested Networks*: Springer; 1987. p. 323-39.
- [51] Balakrishnan H, Chandran BG. Algorithms for scheduling runway operations under constrained position shifting. *Operations Research*. 2010;58:1650-65.
- [52] Ghoniem A, Sherali HD, Baik H. Enhanced models for a mixed arrival-departure aircraft sequencing problem. *INFORMS Journal on Computing*. 2014;26:514-30.
- [53] Sherali HD, Adams WP. A hierarchy of relaxations between the continuous and convex hull representations for zero-one programming problems. *SIAM Journal on Discrete Mathematics*. 1990;3:411-30.
- [54] Sherali HD, Adams WP. A hierarchy of relaxations and convex hull characterizations for mixed-integer zero-one programming problems. *Discrete Applied Mathematics*. 1994;52:83-106.
- [55] Sherali HD, Adams WP. Reformulation-Convexifi-

- cation Technique for Quadratic Programs and Some Convex Envelope Characterizations. A Reformulation-Linearization Technique for Solving Discrete and Continuous Nonconvex Problems: Springer; 1999. p. 297-367.
- [56] Sarin SC, Sherali HD, Bhootra A. New tighter polynomial length formulations for the asymmetric traveling salesman problem with and without precedence constraints. *Operations research letters*. 2005;33:62-70.
- [57] Sherali HD, Sarin SC, Tsai P-F. A class of lifted path and flow-based formulations for the asymmetric traveling salesman problem with and without precedence constraints. *Discrete Optimization*. 2006;3:20-32.
- [58] Sherali HD, Staats RW, Trani AA. An airspace planning and collaborative decision-making model: Part I—Probabilistic conflicts, workload, and equity considerations. *Transportation Science*. 2003;37:434-56.
- [59] Nemhauser GL, Wolsey LA. *Integer programming and combinatorial optimization*. Wiley, Chichester GL Nemhauser, MWP Savelsbergh, GS Sigismondi (1992) *Constraint Classification for Mixed Integer Programming Formulations COAL Bulletin*. 1988;20:8-12.
- [60] Bazaraa MS, Jarvis JJ, Sherali HD. *Linear programming and network flows*: John Wiley & Sons; 2011.
- [61] Desrosiers J, Lübbecke ME. A primer in column generation. *Column generation*: Springer; 2005. p. 1-32.
- [62] Lübbecke ME, Desrosiers J. Selected topics in column generation. *Operations Research*. 2005;53:1007-23.
- [63] Ghoniem A, Sherali HD. Complementary column generation and bounding approaches for set partitioning formulations. *Optimization Letters*. 2009;3:123.
- [64] Blum C, Roli A. Metaheuristics in combinatorial optimization: Overview and conceptual comparison. *ACM computing surveys (CSUR)*. 2003;35:268-308.
- [65] Gendreau M, Potvin J-Y. Metaheuristics in combinatorial optimization. *Annals of Operations Research*. 2005;140:189-213.
- [66] Bianchi L, Dorigo M, Gambardella LM, Gutjahr WJ. A survey on metaheuristics for stochastic combinatorial optimization. *Natural Computing*. 2009;8:239-87.
- [67] Pinol H, Beasley JE. Scatter search and bionomic algorithms for the aircraft landing problem. *European Journal of Operational Research*. 2006;171:439-62.
- [68] Ciesielski V, Scerri P. Real time genetic scheduling of aircraft landing times. *Evolutionary Computation Proceedings, 1998 IEEE World Congress on Computational Intelligence, The 1998 IEEE International Conference on: IEEE*; 1998. p. 360-4.
- [69] Ernst AT, Krishnamoorthy M, Storer RH. Heuristic and exact algorithms for scheduling aircraft landings. *Networks: An International Journal*. 1999;34:229-41.
- [70] Soomer MJ, Franx GJ. Scheduling aircraft landings using airlines' preferences. *European Journal of Operational Research*. 2008;190:277-91.
- [71] Hancerliogullari G, Rabadi G, Al-Salem AH, Kharbeche M. Greedy algorithms and metaheuristics for a multiple runway combined arrival-departure aircraft sequencing problem. *Journal of Air Transport Management*. 2013;32:39-48.
- [72] Kabbani NM, Patty BW. Aircraft routing at American airlines. *proceedings of the agifors symposium*1992.
- [73] Clarke L, Johnson E, Nemhauser G, Zhu Z. The aircraft rotation problem. *Annals of Operations Research*. 1997;69:33-46.
- [74] Mukherjee A, Hansen M. A dynamic rerouting model for air traffic flow management. *Transportation Research Part B: Methodological*. 2009;43:159-71.
- [75] Mercier A, Cordeau J-F, Soumis F. A computational study of Benders decomposition for the integrated aircraft routing and crew scheduling problem. *Computers & Operations Research*. 2005;32:1451-76.
- [76] Mercier A, Soumis F. An integrated aircraft routing, crew scheduling and flight retiming model. *Computers & Operations Research*. 2007;34:2251-65.
- [77] Haouari M, Aissaoui N, Mansour FZ. Network flow-based approaches for integrated aircraft fleet and routing. *European Journal of Operational Research*. 2009;193:591-9.
- [78] Sherali HD, Bae K-H, Haouari M. A benders decomposition approach for an integrated airline schedule design and fleet assignment problem with flight retiming, schedule balance, and demand recapture. *Annals of Operations Research*. 2013;210:213-44.
- [79] Dorndorf U, Jaehn F, Lin C, Ma H, Pesch E. Disruption management in flight gate scheduling. *Statistica Neerlandica*. 2007;61:92-114.
- [80] Braaksma J. Reducing walking distances at existing airports. *Airport Forum*1977.
- [81] Obata T. The quadratic assignment problem: Theory and algorithms (tech. rep.). Troy, NY: Rensselaer Polytechnic Institute. 1979.
- [82] Babić O, Teodorović D, Tošić V. Aircraft stand assignment to minimize walking. *Journal of Transportation Engineering*. 1984;110:55-66.
- [83] Mangoubi R, Mathaisel DF. Optimizing gate assignments at airport terminals. *Transportation Science*. 1985;19:173-88.
- [84] Hassounah MI, Steuart GN. Demand for aircraft gates. *Transportation Research Record*. 1993.
- [85] Bolat A. Procedures for providing robust gate as-

- signments for arriving aircrafts. *European Journal of Operational Research*. 2000;120:63-80.
- [86] Cheng Y. Network-based simulation of aircraft at gates in airport terminals. *Journal of Transportation Engineering*. 1998;124:188-96.
- [87] Haghani A, Chen M-C. Optimizing gate assignments at airport terminals. *Transportation Research Part A: Policy and Practice*. 1998;32:437-54.
- [88] Tang C-H, Wang W-C. Airport gate assignments for airline-specific gates. *Journal of Air Transport Management*. 2013;30:10-6.