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METAHEURISTICS SET

Volume 2

Metaheuristics for Air Traffic Management

Nicolas Durand, David Gianazza
Jean-Baptiste Gotteland
and Jean-Marc Alliot

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coordinated by
Nicolas Monmarché and Patrick Siarry

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Contents

Introduction

Metaheuristics are methods designed to address difficult optimization problems[1]. The term "metaheuristic", coined by Glover when introducing his tabu search method, refers to high-level strategies guiding lower-level heuristics in the search of optimal or near-optimal solutions. Today, metaheuristics cover a wide range of methods that can be categorized in many different ways: population-based or single-solution, mono-objective or multi-objective, nature- or physics-inspired algorithms, hybrid metaheuristics, etc. These categories may overlap. Population-based metaheuristics, for example, include some nature-inspired methods, such as genetic algorithms or particle swarm optimization algorithms. The simulated annealing algorithm, inspired by the annealing process in metallurgy, is an example of metaheuristic iterating on a single individual. Other examples of single-individual metaheuristics include the tabu search, iterated local search and variable neighborhood search.

Many metaheuristics are iterative stochastic methods, in the sense that they rely on some kind of random walk to explore the search space. They also implement a form of "intelligent bias" toward good solutions, based on the evaluation of the objective function at the points sampled during the search. A typical example is the selection of the best-fit individuals in evolutionary algorithms. Another example is the deterministic selection in the differential evolution algorithm: a candidate individual (trial vector) replaces the current individual only if this improves the evaluation of the objective function. Such a mechanism can be viewed as a "greedy" strategy whose aim is to find a better solution as quickly as possible. In addition to randomness and greediness, a third component that may appear in metaheuristics is memory. The promising zones encountered during the search can be memorized so as to intensify the search in these areas. Conversely, non-promising zones can be

1 Large-scale and/or NP-hard problems. In computational complexity theory, the abbreviation NP refers to "non-determistic polynomial-time".

forbidden, as in the tabu search, so as to force the algorithm to explore other areas (diversification).

Beyond the mind-catching analogies with real-world phenomena such as the natural evolution, annealing process, bee swarms, ant colonies or bacterial foraging, it is the right mix of these three components – randomness, greediness and memory – that allows metaheuristics to find a good balance between intensification and diversification of the search. As opposed to exact optimization methods, metaheuristics do not guarantee the optimality of the solutions found. They are, however, powerful tools to tackle difficult problems where other methods fail.

Air traffic management (ATM) is an endless source of challenging optimization problems. Between the moment passengers board the aircraft and the moment they arrive at their destination, a flight goes through several phases: pushback at the gate, taxiing between the gate and the runway threshold, takeoff and initial climb following standard instrument departure procedure, cruise, final descent following standard terminal arrival route, landing on the runway and taxiing to the gate. During each phase, the flight is handled by air traffic control organizations: airport ground control, approach and terminal control and en route control. These control organizations provide services ensuring a safe and efficient conduct of flights, from departure to arrival.

The core of the air traffic controllers' activity is to facilitate the traffic flow through the airspace sectors and on the airport ground surfaces under their responsibility, while avoiding collisions between aircraft. To satisfy this essential safety constraint, they must detect and solve conflicts between trajectories. Such conflicts may occur at any time of the flight, during taxi, takeoff, climb, cruise, descent or landing. The underlying constrained optimization problem is to minimize the deviations from the nominal trajectories while maintaining horizontal or vertical separations between conflicting aircraft. For an airborne aircraft, the air traffic controller can order different types of maneuvers to pilots: horizontal deviations, vertical maneuvers, modified rate of climb or descent or speed adjustments. Conflicts related to runway occupancy can be solved only by optimizing the landing and takeoff sequences. When aircraft are taxiing on the ground, conflict resolution can be achieved by choosing different paths or by making aircraft wait on some taxiways. An additional constraint may then occur: flights must respect their takeoff slots. These slots are traffic regulations enforced by ATM so as to avoid congestion in en route sectors or terminal areas, or at the destination airport. Congestion is actually related to excessive controller workload in some parts of the ATM system. This workload can be alleviated or balanced by several means. One of them is to delay departing flights by allocating takeoff slots. Another is to reroute some flights so as to avoid the congested areas. In addition, the airspace sectors and airways can be designed and managed so as to facilitate traffic flows and alleviate controller workload as much as possible. Strategic activities such as airspace and air route network design are conducted months before the day of operation. The assignment of airspace sectors to controller working positions and the traffic regulation measures – slot allocations and traffic rerouting – can be prepared hours in advance, but they must be adapted in real time considering the effective workload undergone by the controllers.

Several optimization problems have been evoked in this short introduction to ATM: optimal sector design and airways positioning, optimal allocation of airspace sectors to controller working positions, takeoff slot allocation, runway sequencing, conflict resolution for taxiing or airborne aircraft. They are often difficult to model and hard to solve. When building models, one must consider the complexity of the system and the multiple sources of uncertainties (e.g. weather, unknown aircraft parameters and unexpected delays). The problems to solve are not always easy to formulate because they are often complex combinations of interdependent subproblems. In many cases, the size and complexity of the problems being addressed make them hard or even impossible to solve with exact methods.

In this book, we present several applications of metaheuristics to difficult ATM problems. Although metaheuristics applied to ATM is the main focus of this book, we have also tried to present a few cases where specific ATM problems can actually be addressed using other methods, such as computational geometry, clustering techniques, exact tree-search methods and machine learning approaches. We hope this will highlight the advantages and limitations of the different approaches proposed in the literature and by the authors of this book. This should also bring the reader a broader view of what kind of methods can be applied to what problem, sometimes with different problem formulations. In several cases, researchers have proposed hybrid methods combining metaheuristics with exact or heuristic methods to tackle specific problems. Although metaheuristics are not supposed to be problem-specific in general, we will see that real-world problems do sometimes require to replace standard operators – such as mutation or crossover for example, in the case of a genetic algorithm – by problem-specific and possibly hybrid operators.

The book is organized as follows. Chapter 1 describes the ATM context in more detail. The other chapters deal with the different categories of ATM problems being addressed: optimization of air routes (Chapter 2), airspace management (Chapter 3), departure slot allocation (Chapter 4), airport traffic management (Chapter 5) and conflict detection and resolution for airborne aircraft (Chapter 6).

1

The Context of Air Traffic Management

This chapter is a short introduction to the air traffic management operational context.

1.1. Introduction

The aim of this chapter is to present clearly and concisely the current air traffic management (ATM) system, so that readers who are not familiar with it can understand the problems being addressed in this book. More detailed information on the rules and organization in ATM can be found in specific documentations such as [INT 01, INT 08], published by the International Civil Aviation Organization (ICAO).

ATM covers a wide range of activities, including air traffic control (ATC) in which ground-based controllers monitor aircraft and issue instructions to pilots in order to avoid collisions. Between the moment passengers board the aircraft and the moment they arrive at their destination, a flight goes through several phases: push back at the gate, taxiing between the gate and the runway, takeoff and initial climb following standard instrument departure procedure, cruise, final descent following standard terminal arrival route, landing on the runway and taxiing to the gate. During each phase, the flight is handled by ATC organizations: airport ground control, approach and terminal control and en route control. These control organizations provide services ensuring a safe and efficient conduct of flights, from departure to arrival.

The ATM system is highly complex. It handles a huge number of flights and involves many actors: airlines, air navigation service providers (ANSP), airports, national and international regulatory authorities, etc. In 2013, the ATM system controlled 9.6 million flights operating under instrumental flight rules (IFR) in

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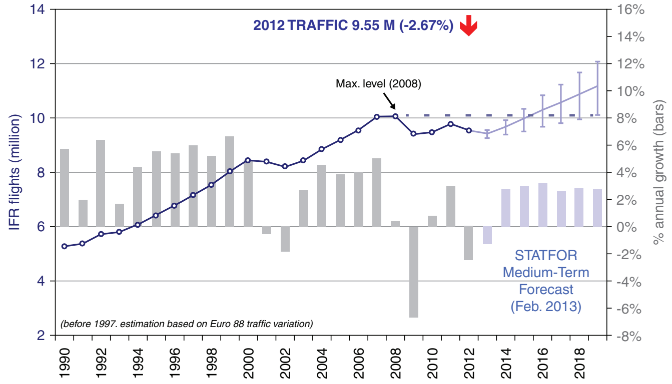
Europe and 15.1 million in the United States. The Federal Aviation Administration estimates that its National Airspace System is in charge of 4,000–6,000 flights simultaneously[1] during peak hours.



Sources Eurocontrol/Statfor (ESRA2008).

Figure 1.1. *Air traffic forecast in Europe*

In terms of future evolutions, the Asia-Pacific region is anticipated to undergo a rapid growth in traffic volume. In North America and Europe, the growth rate is expected to weaken. However, the global trend still points toward a traffic increase, as shown in Figure 1.1.

1.2. Vocabulary and units

The aviation community uses specific units and a specific vocabulary that needs to be introduced before describing the ATM system. An index of acronyms can be found at the end of the book.

Altitudes are expressed in feet (ft), or in flight levels (FL), with 1 FL $=$ 100 ft. There are several definitions of altitude, but the most widely used is the geopotential pressure altitude, computed from the static air pressure p measured onboard the aircraft. FL are defined in reference to the isobar surface $p_0 = 1,013.25$ hPa.

Distances are expressed in nautical miles (NM), with 1 NM $= 1,852$ m. Velocities are expressed in knots (kts), with 1 kts $=$ 1 NM/h.

The aircraft speed in the air is measured through dynamic pressure sensors. The true airspeed (TAS) is the actual aircraft speed in the air. The calibrated airspeed

1 http://www.fly.faa.gov/Products/Information/information.html.

(CAS) is the TAS that would be necessary at mean sea level to obtain the same dynamic pressure than that measured onboard the aircraft. If we neglect the instrument errors, the CAS is the speed used by pilots when operating their flight, together with the Mach number, which is the ratio of the TAS and the speed of sound in the air. Typically, a climbing aircraft will follow several climb segments at constant CAS, followed by a climb segment at constant Mach number, at high altitudes.

Aircraft fly in the air, and the air is in movement above the Earth's surface. We also define velocity relative to the Earth's surface, called the ground speed, expressed in knots.

1.3. Missions and actors of the air traffic management system

The objective of ATM is to ensure safe and efficient flights, from departure to arrival. This mission is carried out by a number of national or international organizations that provide different services to the airspace users.

There are different kinds of airspace users. General air traffic includes commercial flights, private flights for leisure or for affairs, special flights for geographic data collection, meteorological studies or any other scientific study, drones, gliders, aeromodelling, etc. Military air traffic includes flights with specific missions such as flight combat training, surveillance and in-flight refueling, and other military missions.

Several kinds of services can be provided to the users:

– ATC services: 1) prevent collisions between airborne aircraft; 2) on the ground between aircraft and obstacles; 3) organize and expedite air traffic flows;

– flight information services provide useful information and advice to ease safe and efficient traffic;

– alerting services notify relevant organizations regarding aircraft in need of search and rescue aid, and assist such organizations as required.

While information services are not responsible for trajectory separation, control services are. Therefore, air traffic controllers issue instructions to pilots to maneuver the aircraft laterally, vertically or by adjusting speed or rate of climb/descent. When only the flight information service is provided, pilots take charge of collision avoidance.

The control, information and alert services are provided to users by ANSP. There are many actors interacting with one another in the ATM system: airports, air traffic control centers (ATCCs), airline operators, national and international regulatory authorities, military control centers and authorities, meteorological services, etc.

In order to avoid airspace or airport congestion, it is necessary to organize and regulate the traffic flows. This continental-scale network management is carried out in Europe by the Eurocontrol Network Management Operations Center (NMOC) that enforces air traffic flow management (ATFM) regulations when required so by ATC units anticipating overloads. In the United States, this regulation takes the form of ground delay programs (GDPs) concerning each one or several airports in a same area. These GDPs are coordinated by the Air Traffic Control Strategic Command Center (ATCSCC). Similar organizations exist in other parts of the world where the traffic is dense enough to require such flow regulations.

1.4. Visual flight rules and instrumental flight rules

Flights can be separated into two categories, depending on the level of equipment of the aircraft and level of qualification of the pilots. A flight may operate under visual flight rules (VFR) or instrumental flight rules (IFR).

Under VFR, the pilot must maintain a sufficient distance to the neighboring clouds and obstacles. He/she can fly only if the meteorological conditions are compatible with VFR, especially concerning the visibility. These flight rules are designed for light aviation, where the basic "see and avoid" principle is applied to maintain separation from other aircraft.

IFR are less hampered by degraded meteorological conditions. Because IFR flights are allowed to fly in low visibility conditions, they are generally controlled by an ATC unit that is in charge of ensuring separation from other IFR or VFR flights.

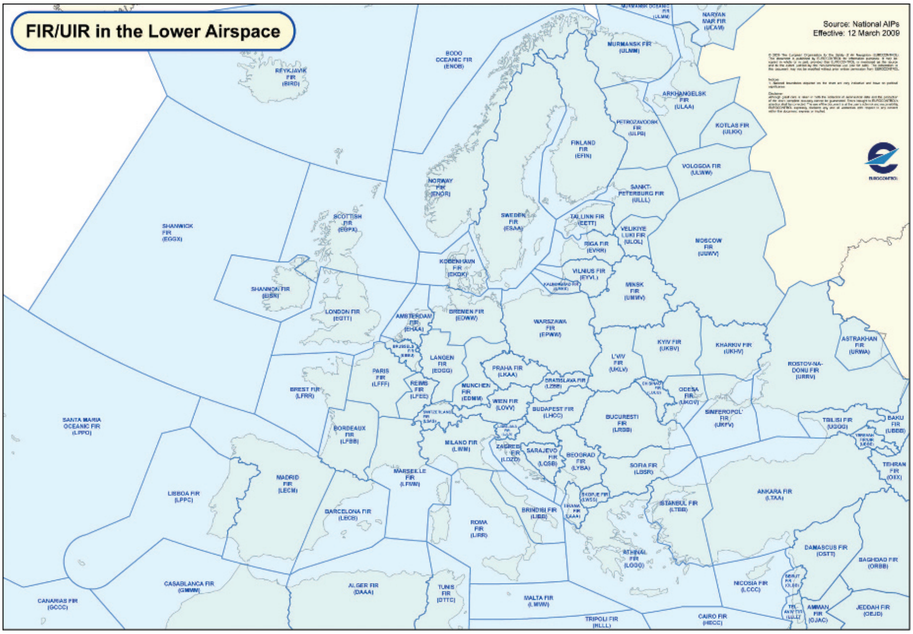
1.5. Airspace classes

Several classes of airspace (from A to G) determine which services are provided to which types of flight. For example, only IFR flights can fly in Class A airspace, where the ATC service is provided to all IFR flights. In Class B airspace, IFR and VFR flights are admitted. The control service is provided to all flights and separation from other aircraft in ensured for all flights (IFR and VFR). Both IFR and VFR flights are allowed to fly in Class C airspace. However, separation from other aircraft is only ensured for IFR/VFR or IFR/IFR pairs. VFR flights are separated from IFR flights, but they only receive flight information relative to the other VFR flights and must ensure their own separation from these VFR flights. The following classes are similarly defined, with less and less services provided to flights. In Class G airspace, only the flight information service is provided and only for the flights that request it.

1.6. Airspace organization and management

1.6.1. *Flight information regions and functional airspace blocks*

Flight information regions (FIRs) are managerial divisions of the airspace into large regions where the air navigation services (control, information, alerting) are provided to airspace users. FIRs cover the totality of the Earth's atmosphere. In some countries, there is only one FIR covering all the airspace within their borders. This is not always the case, however. Some countries may have their national airspace included in a wider FIR covering neighboring countries. Other countries have divided their airspace into several FIRs. This is the case in France, for example, where the national airspace is divided into five FIRs. Figure 1.2 shows the airspace partitioning into FIRs in Europe.

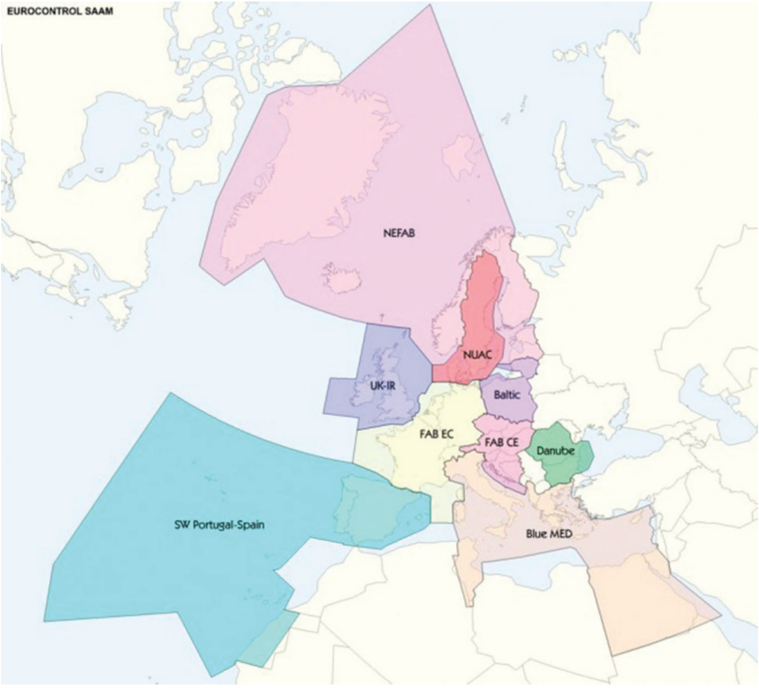


Source Eurocontrol

Figure 1.2. *FIRs in Europe*

The FIR boundaries are designed by the national authorities. Some FIRs are split vertically. In such cases, the lower part keeps the name FIR whereas the upper part is called an upper information region (UIR).

As a consequence of Europe's history, a great number of FIRs cover the European territory. The Single European Sky legislative package aims at harmonizing the ATM system, making it less dependent on the national boundaries. For that purpose, FIRs covering different national airspaces are grouped into larger units, called functional airspace blocks (FABs). Figure 1.3 shows the FABs in Europe. For the time being, the different FIRs within an FAB are not fully integrated yet, but there is a closer coordination of the ANSP within a same FAB.



Source Eurocontrol

Figure 1.3. *Functional airspace blocks in Europe. For a color version of the figure, see www.iste.co.uk/durand/atm.zip*

1.6.2. *Lower and upper airspace*

In Europe, the airspace is split vertically, defining a lower airspace and an upper airspace. The boundary between upper and lower airspace is usually at FL 195, which means a pressure altitude of $19,500$ above isobar $1,013.25$ hPa. However, in some countries, lower and upper airspace may be divided at a different FL. For example the UIR of the Maastricht control center, which is in charge of the airspace above Belgium, Luxembourg and the north west of Germany, starts at FL 245. In France, there is only one UIR, above FL 195, and five FIRs below FL 195, although in practice the portion of upper airspace above each FIR is controlled by the ATCC in charge of this FIR. In the United States, there is no UIR but the upper airspace sectors start at FL 240.

1.6.3. *Controlled airspace: en route, approach or airport control*

In the airspace where control services are provided to users, some volumes are dedicated to aircraft flying in the vicinity of airports, and some others are dedicated to en route flight between departure and destination.

The airspace volume around the airport is a control zone (CTR) for aircraft flying at low altitude, close to the airport runway. Above the CTR, a larger zone called terminal maneuvering area (TMA) in Europe or terminal control area (TCA) in the United States is dedicated to aircraft following arrival or departure procedures. It may cover several airports, in dense areas. Figure 1.4 shows the Paris TMA, as an example of such zones, with top and side views illustrating the airspace classes for each volume of airspace in the TMA.

The TMA (or TCA) is a transition between airports and the network of airways defined in the en route airspace. To summarize, there are different types of control activities, depending on the airspace volume being controlled:

– airport control, which includes tower control for runway operations and ground control for aircraft taxiing on the airport surface;

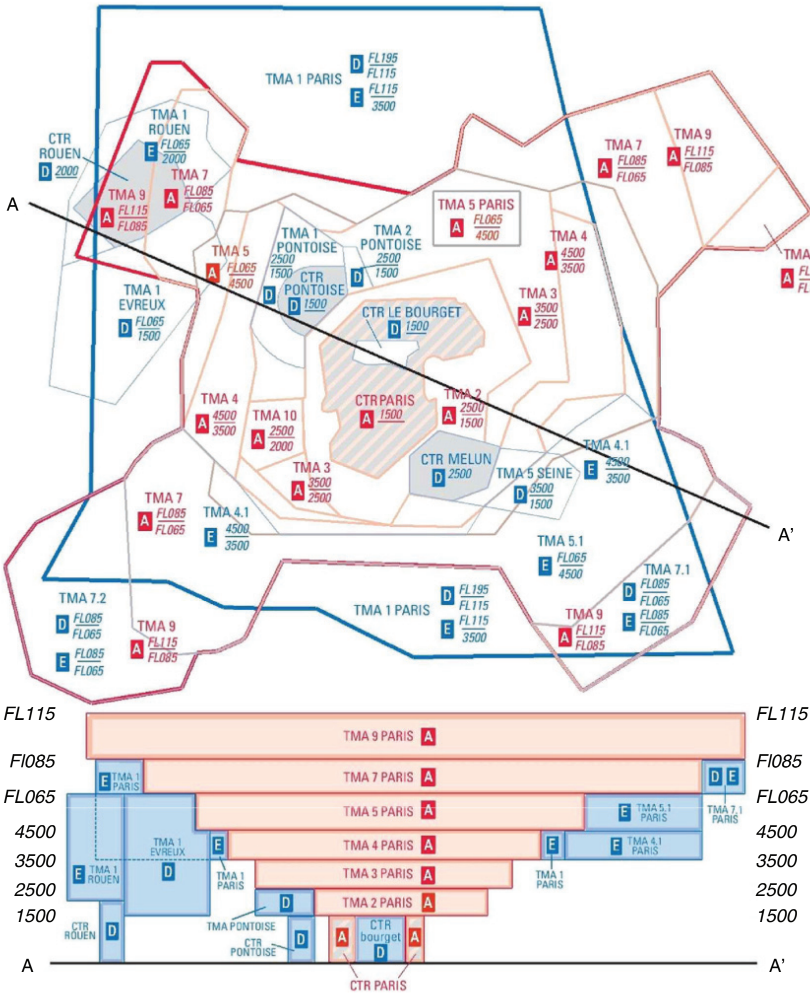
– approach control, for departure and arrival procedures;

– en route control, for flights following airways from departure to destination.

These three kinds of control activities are illustrated in Figure 1.5, where some radio-navigation aids, radars and communication equipment are also shown. A control tower and an en route ATCC are also represented. The control tower is in charge of aircraft separation in the neighborhood of the runway. It sequences takeoffs and landings, and prevents collisions of aircraft taxiing between the gates and the runway. The ATCC is in charge of en route traffic. The approach control service can be provided by an ATC unit located on or near the airport, for big airports, or the regional ATCC center, for small airports.

1.6.4. *Air route network and airspace sectoring*

Aircraft flying in the lower or upper en route controlled airspace follow predefined airways. The air route networks might be different in the upper and lower airspaces. Aircraft can deviate from their intended routes when instructed so by air traffic controllers, in order to keep separation with other aircraft or to avoid convective weather.



Source DGAC/SIA

Figure 1.4. *Top and sectional view of Paris TMA (2011). For a color version of the figure, see www.iste.co.uk/durand/atm.zip*

As a human controller can only handle a limited amount of traffic, the airspace is divided into sectors, which can be seen as the smallest airspace unit. An air traffic controller is only in charge of the traffic flying through the airspace sectors assigned to its working position.