French Civil
Aviation
Authority

Civil Aviation
Technical Center

September 2020

Airport Capacity

Technical guide

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

MINISTÈRE
DE LA TRANSITION
ÉCOLOGIQUE
ET SOLIDAIRE

Ministry for an Ecological and Solidary Transition

www.stac.aviation-civile.gouv.fr

dgac
STAC

French Civil Aviation Authority

Civil Aviation Technical Center

September 2020

Airport Capacity

Technical Guide

Civil Aviation Technical Center

Capacity, Environment, Master Plans Department

Authors:

Roland DEROO MASSON

Senior Project Manager

Alexandre GAMA

Senior Project Manager

Roland Deroo Masson and Alexandre Gama *are both project managers within the Aerodrome Safety and Capacity Division. They share their expertise in the field of simulation and airport capacity with different institutional and industrial partners.*

Roland Deroo Masson, a state engineer joined STAC after a year specialising in the field of decision aids at the National Conservatory of Arts and Crafts and a project at Paris Charles de Gaulle airport's CDM programme.

Alexandre Gama is also a state engineer and joined STAC after having led research connected to the integration of environmental issues in airport simulation tools. He has a broad knowledge of flight operations as he also holds a pilot licence with instrument rating.

In addition to their individual areas of expertise, they are both international experts and represent the DGAC within international organisations (ICAO, EUROCAE), and in entities that bring together users of airport simulation tools in Europe and across the globe.

Summary

With the continuous increase in global air traffic over the last few decades (3.7 billion passengers transported in 2016 worldwide), the problem of the network's capacity and therefore its infrastructure has become a major challenge. Without a policy to accompany this growth, the saturation of the entire system is inevitable in the long run.

The objective of this guide is to address the question of an airport's capacity by considering it as a whole complex system. This guide covers the definition of the concept itself, then discusses the elements that influence it, and presents the methods available to evaluate it and the means that can be implemented to improve it.

Keywords

Capacity, airport, terminal, operational capacity, sustainable capacity, maximal capacity, level of service, capacity assessment, improvements, simulation, analytical tools

Preface

Airport capacity has been the common thread throughout my career in civil aviation. The topic came to prominence when air traffic increased significantly in the 1980s after 15 years of a kind of stagnation as a result of oil price crises in 1973 and 1979.

Previously, airport capacity was an issue for technicians specialized in infrastructure or air traffic control; however, the saturation of air traffic in 1988 brought to light the economic, societal and environmental and therefore political aspects of airport capacity.

This had a significant impact in Europe in particular, where the European Civil Aviation Conference launched the APATSI (Airport Air Traffic System Interface) programme to reduce congestion in and around airports.

As part of this programme, were created the European observatory for delays was created, a database of the current and future capacities of the 100 largest European airports, and working groups to improve operating procedures, drive innovation, exchange good practices. Together with the CFMU, these were the forerunners of the European Network Manager currently in force.

It was at this time that the concepts of HIRO, AMAN, DMAN which are currently deployed in large airports were conceived, that the A-SMGCS system presented in this manual was standardized and that the Local Runway Capacity Teams were formed to later become the base of the A-CDM concept.

As the director of this programme, through a great number of conversations with all of the actors in air transport I have become aware of the difficulty that these have in understanding each other when they discuss airport capacity and how to increase it because of their different perspectives and timeframes.

The manual created by the Civil Aviation Technical Centre (STAC) is the first document at an international level in 30 years to present the issue of capacity in its entirety. It achieves this by approaching the complex system that is an airport in view of the service provided and the quality of this service to users, operators, and private and institutional managers.

It then details the various aspects and means for evaluation and improvement in a clear and simple way. It is a valuable reference tool for implementing a collaborative and harmonious management of airport capacity in the short, medium and long term.

It has been a great pleasure to read it and edit this preface and I hope you will enjoy reading it as well.

Jean-Louis **PIRAT**

Table of contents

Introduction

With the continuous increase in global air traffic over the last few decades (3.7 billion passengers transported in 2016 worldwide), the problem of the network's capacity and therefore its infrastructure has become a major challenge. Without a policy to accompany this growth, the saturation of the entire system is inevitable in the long run.

This accompanying policy is reflected in the development of infrastructures, used systems and operating procedures. Its aim is two-fold as it relates to not only developing the existing network, but also using it in the best way.

To be able to develop an efficient system, it is essential to assess its capacity, which means the amount of traffic that it can handle. This capacity, in comparison to the actual or anticipated demand makes it possible to plan for what is required in the future in the best way. Thus, it is possible to create a viable development plan from an economic, environmental and societal point of view.

The objective of this guide is to address the question of an airport's capacity by considering it as a whole complex system. This guide will cover the definition of the concept itself, then discuss the elements that influence it, before presenting the methods available to evaluate it and the means that can be implemented to improve it.

The focus of this document is on one hand on the different parameters and elements that influence airport capacity, and on the other hand on the different methods for evaluating capacity. This document does not aim to lay down a practical guide for calculating infrastructure capacity step by step, but to provide a solid foundation from a methodological stand point. This guide is intended to cater for all, both in terms of its content and its format.

1. Airport capacity: problem statement and definition

1.1. Problem statement

Infrastructure capacity is vital information for the various actors involved on a platform, such as the airport operator, air traffic control, the regulatory authority (the state, the local communities) and even airlines. There may be various aims at different decision-making levels:

- Strategically, in the long term, to make it possible to plan investments;
- Tactically, in the medium term, for example to assess the opportunity to change operating practices without changing the infrastructure, or to put in place demand management;
- Operationally, to adapt in real time to the actual traffic mix in the very short term.

In fact, information such as the amount of traffic that the infrastructure can accommodate, the predicted saturation date of the infrastructure given the anticipated traffic or even weak links can be determined based on capacity in order to focus and optimise investments.

It should first be noted that the idea of capacity differs depending on the issues and time periods associated with them. This guide will come back later to the different definitions of capacity depending on the context in more detail.

To evaluate the capacity of an airport as a whole, it is necessary to determine the capacity of each of the links that it is made up of. Generally, the following sub-groups can be distinguished:

- Land access (road transport, parking, public transport);
- Terminals (passenger and freight);
- Aircraft movement areas (apron + manoeuvring area);
- Aircraft access (terminal manoeuvring areas).

By determining the capacity of each of these sub-groups, it is then possible to determine the capacity of the whole airport system in relation to the interfaces between these different sub-groups.

This guide focuses on the capacity of terminals and aircraft movement areas. It will also introduce the issues faced in terminal manoeuvring areas, but will not deal with land access, which is not handled by the civil aviation authority.

1.2. Systemic definition of an airport

An airport may be considered as a system in its simplest definition, i.e. a set of elements organised in a structure. In addition, the airport system itself is made up of sub-systems where the same definition applies, which are all links in the airport chain.

Figure 1 shows the airport system and its main sub-systems dedicated to handling flows. These sub-systems can also be broken down into secondary levels, etc.

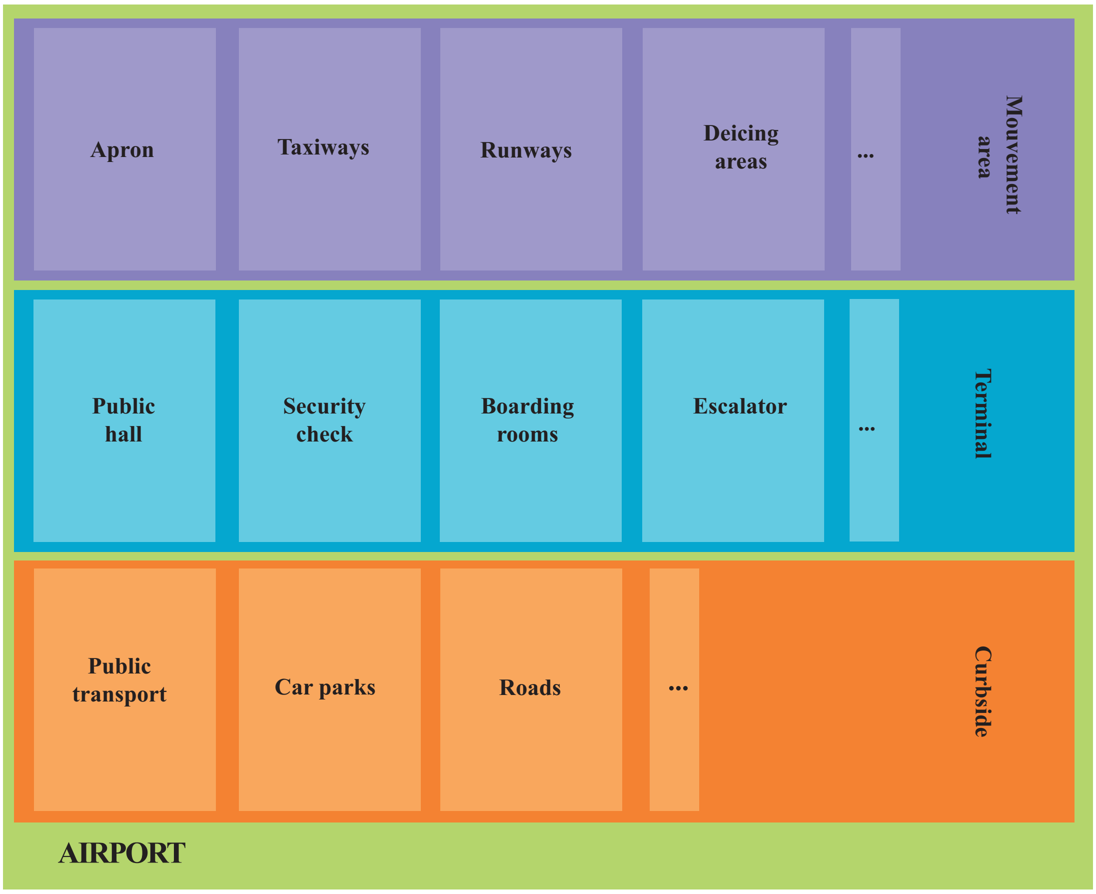


Figure 1: Diagram of the airport system and its sub-systems

More specifically, airports are systems for handling flows (of aircraft, of passengers, of baggage, of freight, of vehicles), the role of which is to allow for the processing of passengers, of baggage and/or freight in "packages" loaded onto or out of the aircraft. The sub-systems it is made up of can be considered as networks formed of three types of elements:

- **Links**, the role of which is to make it possible to move a flow without changing its intrinsic characteristics. For example, there are spaces exclusively dedicated to movement such as staircases, corridors, escalators, etc. in terminals and taxiways in aircraft movement areas.
- **Processors**, which bring about a transformation changing the characteristics of the flow by means of a control or a transaction. For example, a security screening point transforms a flow of "non-secure" passengers into a flow of "secure" passengers, and a runway transforms a flow of aircraft on the ground into a flow of aircraft in the air.
- **Reservoirs**, the role of which is to store the elements of a flow. Generally, reservoirs are found upstream of processors. They cover for example the waiting areas before screening points in terminals, or the taxiways feeding the runway where it is possible to hold aircraft before they enter the runway protection area.

Some processors play the role of an interface between two sub-systems. This is the case, for example, with the esplanade between the passenger access and the terminal, and with the jetways between the terminal and the aircraft.

In terms of systemic analysis, an airport is therefore a logical progression of links, reservoirs and processors, which are implemented one after another, allowing people or freight to board or leave the aircraft.

Based on these elements, it is possible to provide an initial definition of airport infrastructure capacity. It corresponds to the maximum number of entities that can be "processed" by the links, reservoirs and processors within a given period of time in defined operating and level of service conditions. More specifically:

- for links, it is the number of entities that can be moved;
- for reservoirs, it is the number of entities that can be held, taking into account the inflows and outflows levels;
- for a processor, it is the number of entities that can be transformed.

While this view of an airport system is relatively abstract, it has the benefit of being able to be generalised for any system or sub-system in question, and makes it possible to identify any bottleneck and its type. Effectively, it remains valid for considerations at both aircraft and terminal level, or for the terminal considered as a whole or for a particular service (security screening, check-in, etc.). For example, if we are interested in the terminal as a whole, the entirety of the security screening point can be considered as a reservoir (i.e. a holding area with an inflow and outflow level), or in detail with a reservoir first (the queue), a link (which links the queue to the checkpoint) and then a processor (the checkpoint that transforms a "non-secure" passenger into a "secure" passenger).

The airport system itself is also connected to other elements in its surrounding environment. It is for instance linked to the terminal manoeuvring area (the approach airspace) on one side, and to the urban area it is located in on the other. It is in no way a closed system, but rather one that exists within a much larger context. This means various issues related to a context extending well beyond the physical borders of the airport need to be addressed in order to obtain a satisfactory assessment.

1.3. "Standardised" definitions of capacity

1.3.1. Terminology

The term capacity is regularly used imprecisely to refer to various parameters within an infrastructure. Thus, the concepts of demand, supply, throughput and capacity are often confused when capacity is being discussed, which can lead to misunderstandings and difficulties in communicating with different stakeholders. These terms are actually defined as follows:

- **Demand**: this is the quantity of traffic planned at a particular moment before operations.
- **Supply**: this is the quantity of traffic the stakeholders deem to be manageable by the system in a given situation.
- **Throughput**: this is the quantity of traffic that has actually flowed through the system over a period of time.
- **Capacity**: this is the quantity of traffic that can theoretically be processed by the system.

It is useful to note that these deliberately simplified definitions are provided for illustrative purposes in order to highlight the differences between these concepts. There are actually numerous variants of each definition depending on the standpoint from which the system is considered. In the rest of this chapter, the concept of capacity will be described in more detail.

It is also interesting to note that in an "ideal" system, the demand, the supply, the throughput and the capacity are merged into a single value. The supply is thus set at its maximum value, which is the capacity, the demand fulfills the entirety of the supply, and the throughput observed effectively matches exactly what is theoretically achievable.

However, in a real system, notable differences can be seen between all of these values. The capacity may be higher than the supply in order to guarantee operating margins, the demand may be higher than the capacity, or the throughput may occasionally be higher than the initial demand. The supply may also be set higher than the capacity in order to guarantee a continuous feeding of the system, even if this occasionally generates delays.

1.3.2. Selected definitions

There are different definitions of airport capacity in the literature, each with their own distinctions and fields of interest. For greater clarity, only the following definitions that are generally found in the more recent literature are used in this guide:

- **Maximum capacity** C_m (or saturation capacity): this is the quantity of traffic that can flow through an infrastructure in saturation conditions (i.e. a continuous demand), in compliance with the applicable regulations but with no consideration regarding the resulting level of service (for example delays).

- **Operational capacity** C_o: this is the quantity of traffic that can flow through an infrastructure in compliance with the applicable regulations and taking into account a defined level of service (for example an acceptable delay or operational margins, the following chapter will cover this concept in more detail).
- **Sustainable capacity** C_s: this is the quantity of traffic that can flow through an infrastructure in a sustainable way. This refers to the ability of operators to maintain a level of performance over a long period of time and to reproduce this level of performance accounting for variability sources such as human factors.

These definitions benefit from being simple and easy to understand by all stakeholders. In a simplified manner, the following relationship exists between the three definitions:

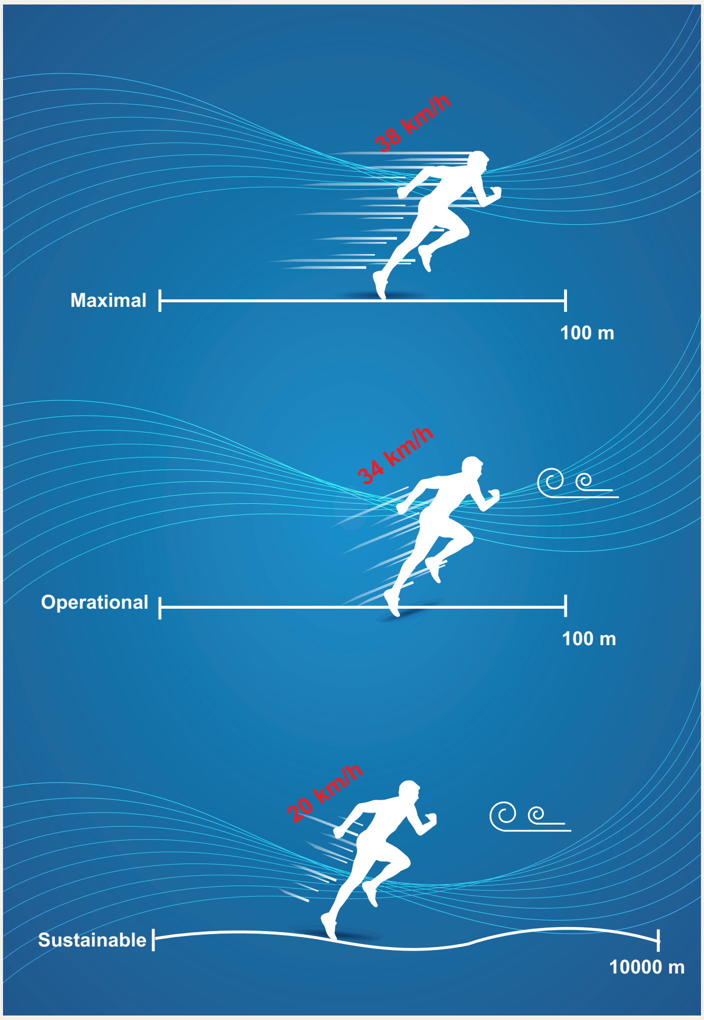
$$C_m \geq C_o \geq C_s$$

It should be noted that while the three definitions are different, in practice, local operating conditions may lead to a convergence of the three values. At certain airports, all available capacity is used operationally, in which case, operational and maximum capacity amount to the same thing. Conversely, some platforms have a maximum capacity that is particularly difficult to achieve, and even more so to maintain over long periods of time. This is the case in particular at airports with little air or ground space to allow for the regulation (change of aircraft sequence order) of aircraft traffic.

At certain airports the concept of "declared capacity" is also introduced. This is a value that is provided by local actors (in France, this is generally by the air navigation service provider) which combines all of the capacity values and corresponds to the displayed infrastructure capacity that is shared with other stakeholders. This value is provided in particular to EUROCONTROL (the European organization responsible for managing aircraft movements within wider Europe) to allow for more efficient management of flows and to avoid the issue of congestion in European airspaces. It is important to note that in France this concept is different to what is usually known as "declared capacity" in English, which in the context of this guide (originally in French) will be referred to as "planning capacity" instead (see chapter on the regulatory framework).

MAXIMUM, OPERATIONAL AND SUSTAINABLE CAPACITY: LOOKING DEEPER INTO THESE THREE DEFINITIONS

To better understand these three concepts, we can provide an analogy with a runner. In this example, the "capacity" corresponds to the speed that the runner could reach. The diagram below illustrates the different definitions:



- *In the first case, our runner attempts to reach their maximum speed in perfect conditions, i.e. an ideal track in optimum meteorological conditions. They reach 38 km/h. The conditions required to reach this speed can almost never be met in a normal environment.*
- *In the second case, our runner attempts to move as quickly as possible on a path that is not ideal, which is represented by slopes and unfavourable meteorological conditions (a headwind). Here they reach 34 km/h, a speed that they can only maintain for a short distance.*
- *In the last case, this time our runner sets a pace that provides them with significant endurance to be able to run a further distance, even on a path that is not ideal and in meteorological conditions that are not optimal. Here they reach 20 km/h, a speed that they can maintain for the whole distance.*

While this analogy is simplistic, it illustrates the three different definitions, as well as the benefits that each might represent in the evaluation of an airport system.

1.3.3. Scope of definitions

While attempting to address the question concerning infrastructure capacity, the first issue is deciding **which** capacity should be determined.

The maximum capacity is a known reference value that is impossible to exceed. Therefore, if the demand is higher than this, it will not be possible to process it without generating delays. In order to evaluate the opportunity to implement new infrastructures in the medium-long term (new terminals, new runways, etc.) it is however often more appropriate to determine the operational capacity and correlate this with traffic forecasts in order to evaluate a predicted saturation level. These two complementary concepts are at the heart of airport planning documents (master plans) that are essential for planned, intelligent and rational development of installations and airport sites. The evaluation of capacity carried out in these planning documents, confronted with traffic forecasts, is the basis of the definition of future requirements.

When performing a capacity analysis aiming at establishing coordination at an airport (see chapter on the regulatory framework), i.e. the determination of slots that can be allocated to airlines on a platform, determining the operational capacity or the sustainable capacity is generally useful in order to offer a number of slots that the airport is actually in a position to handle. It should be noted that in certain case studies, the specific nature of the question posed may require a bespoke approach and more case specific concepts of capacity.

1.4. Regulatory framework

The concept of capacity has very little presence in either national or international regulations. Generally, the capacity is merely the result of other elements which do have numerous regulatory texts themselves, usually because of the major safety issues they imply (e.g. the space between two aircraft, or even obligatory security measures during passenger screening).

1.4.1. Limitation of airport nuisance

The regulator may be called upon, in collaboration with other local actors, to impose limitations on airport capacity when aircraft movements cause nuisance issues such as noise or emissions of pollutants. As an example, some airports are subject to a limit on the maximum number of aircraft movements (take-offs and landings) that can be carried out over a defined period of time. This is the case at Orly, where the annual number of slots is limited to 250,000 over two consecutive aeronautical seasons (summer and winter) and where a night-time curfew prohibits movements during certain hours at night.

1.4.2. Coordination or facilitation procedure

In the case of congestion of an infrastructure, the main regulatory tool of the legislator for taking action is **coordination** (IATA Level 3) and its lower level, **facilitation** (IATA Level 2). This is a means of managing the demand of airlines by setting a maximum supply value, which is referred to as **planning capacity**.

Airlines are required to have slots in order to be able to carry out movements at coordinated airports. The slots are allocated by a coordinator designated by the legislator. In France this is the independent association **COHOR**[1] which is tasked with allocating slots to airlines and ensuring their proper use.

[1] Association for the coordination of schedules. Created in 1995, the association has the aim of allocating time slots and ensuring their proper use. Its members are representatives from airlines and airport operators.

In the event of a breach of the rules regulating the coordination of a platform (movements without slots, or at a different time to that of the allocated slot), the airline may be sanctioned by the competent departments of the State. Schedule facilitation incorporates the principles of coordination, without the restrictive aspects (there is no requirement to have a slot to carry out a movement, but airlines are strongly encouraged to do so). The success of the facilitation process therefore relies on good cooperation between airlines and the entity responsible for slot allocation.

In Europe, the European Regulations 95/93, 793/2004 and 545/2009 (which amended the first in part) set the conditions and methods for implementing coordination and facilitation at airports. In particular, the regulation requires the capacity to be assessed *based on commonly recognised methods, which shall determine any shortfall in capacity, taking into account environmental constraints at the airport in question. The analysis shall consider the possibilities of overcoming such shortfalls through new or modified infrastructure, operational changes, or any other change [...]. Where capacity problems occur, [...] the Member State shall ensure that the airport is designated as coordinated for the relevant periods only if the shortfall is of such a serious nature that significant delays cannot be avoided at the airport, and there are no possibilities of resolving these problems in the short term*.

The implementation of coordination is therefore generally considered as a "last resort" in order to counteract a congestion problem (i.e. the planned demand being greater than the capacity). When it is possible and appropriate, it will often be preferable for airport operators to increase the capacity of their infrastructures in line with the evolution of the demand rather than resorting to coordination, which means avoiding congestion by refusing part of the demand but also by depriving themselves of the associated air revenues.

A coordination procedure may be permanent if the issue of congestion is recurrent throughout the whole year, during one season for airports with seasonal traffic (winter season or summer season), or occasionally over a shorter period in the case of specific events.

In some cases, implementing coordination may be wise in anticipation of an exceptional event. For example, this was the case in France in 2016 with the organisation of the European football championship, where preventative measures were taken in order to anticipate the increase of traffic at airports close to the stadiums used for the event.

COORDINATED AIRPORTS IN FRANCE AND ACROSS THE WORLD

There are four airports in France that are coordinated the whole year (winter season and summer season):

- ***Paris-Charles-de-Gaulle***
- ***Paris-Orly***
- ***Lyon-Saint-Exupéry***
- ***Nice-Côte d'Azur***

For these airports, before each season, the regulator sets the coordination parameters in collaboration with local actors in order to take into account the developments in the infrastructure and the operational tools, which make it possible to regularly improve the capacity of the infra-structure and therefore also the threshold set by the regulator. The coordination criteria are specific to each airport, for example including conditions on passenger flows per hour in Paris CDG terminals, restrictions on aircraft parking in Nice, or even the curfew imposed in Orly in the middle of the night.

Chambéry, Annecy, Figari and Nantes are four airports declared as schedules facilitated airports. The first two fall under a single common facilitation order as their access air routes are greatly interweaved (the terminal manoeuvring area is shared by the two airports). At the first three airports, facilitation is seasonal (winter for Chambéry and Annecy, summer for Figari) given the very seasonal nature of the demand mostly generated by tourism in these places.

Cannes airport is also coordinated each year during the Formula 1 Monaco Grand Prix which brings crowds to the Côte d'Azur.

Not all countries across the world have the same practices when it comes to the coordination of platforms. In the USA, only two airports are coordinated (New York JFK and Newark) and two others (Chicago O'Hare and San Francisco) are schedules facilitated. Access to other airports is therefore given freely to airlines, with demand self-regulating based on the supply and the amount of delay experienced.

In total in 2018, 293 airports were declared as facilitated or coordinated for all or part of the year.

1.5. The role of each stakeholder regarding capacity

The role and contributions of the different stakeholders may vary depending on the type of question that is asked (in particular what capacity is considered) and, more specifically, depending on who has asked the question and why. In a simplified manner, in the context of capacity analysis, we can classify the actors on a platform according to three distinct categories:

- The users who use the system;
- The operators who operate the system (who process the users);
- The developers who design and plan the development of the system.

The following actors are the main participants in discussions regarding capacity.

The **operator of the infrastructure** is always an essential participant as it is responsible for managing the infrastructure, its operation and sometimes also its development. This is the case for the terminal area in particular, even though the operator has the option to delegate parts of the operations to specialised companies, such as security screening companies. The operator is therefore very likely to be interested in the evaluation of the capacity of its infrastructures whether in their entirety or from a specific standpoint, as the results will allow them to adapt its management practices or to plan ahead for the implementation of new infrastructures.

The **air navigation service provider** is also an essential partner in issues relating to aircraft movement areas. It is indeed the main entity responsible for managing the aircraft movements on the ground and in the airspace. It therefore has knowledge of the platform’s operating procedures (where aircraft movements are concerned) and is also responsible for defining these procedures. It is therefore concerned with questions pertaining to the capacity of the movement area and the terminal manoeuvring area of the platform both as a provider of the data required for conducting the analysis, and also as a recipient of the results.

As mentioned above, certain processes may be delegated to **specialised companies** by the operator. When investigating the capacity of such processes, it is therefore natural to involve the specialised companies in charge during the analysis, since while the operator establishes the rules to be followed by these companies, the latter are ultimately the ones who have the operational and tactical control of the processes. Such subcontractors are regularly found in charge of the security screening or the ground handling of aircraft at their stands.

State services are also important participants; both those involved as economic regulators or regulatory authorities, as well as those with operational control of some processes, in particular in terminals (customs, border control, air transport police). Some State services may also be involved in order to provide specific **data, such as meteorological data.**

Airlines have their own operating procedures and instructions, which are often not well known by other actors on the platform. Within the scope of a capacity analysis, it is desirable to survey airlines to avoid creating infrastructures or operating procedures that do not suit them.

Passengers may also be relevant participants, in particular in order to gather data making it possible to most accurately model their behaviours and preferences. They may also be a beneficial source in terms of feedback for the evaluation of the level of service.

The cooperation between these different actors is essential in order for a project relating to airport capacity to be able to move forward at the correct pace and in the right direction. The various participants are very much intertwined and it is essential that all move forward together while being fully aware of the situation of each of the others. In order to facilitate this collaboration between the parties involved, the A-CDM[2] *(Airport – Collaborative Decision Making)* concept was developed in Europe from the start of the 2000s. The main aim is to allow partners to work together and to make better decisions based on more precise information, where each piece of information has the same significance for everyone. Such collaboration relies on the sharing of best practices between the actors so that the preferences and constraints of each stakeholder can be recognised at present and in the future. At the start of 2018, close to thirty European airports have obtained the A-CDM label from EUROCONTROL, and around a dozen others will join them by 2020.

[2] For more information on the subject, please refer to Doc 9971 Manual on Collaborative Air Traffic Flow Management published by the ICAO.

2. Level of service, definition and impact on capacity

The level of service is an important element that comes into play when defining infrastructure capacity. As introduced in the previous part, this element is present in two different definitions of capacity (operational and sustainable). The level of service reflects the balance between capacity and demand, i.e. the way in which an infrastructure responds to the expectations of its users in terms of comfort and efficiency. This demand corresponds to a reference traffic level and mix which should be established jointly with all of the actors involved. The reference traffic is generally peak traffic deemed characteristic of usual operations on the platform.

The level of service can be considered as a lever for action of the infrastructure manager. The capacity of a given system depends on the level of service agreed by the operator, for example a given terminal could process 1,000 passengers an hour in good conditions (comfort, punctuality, etc.), or 1,500 with a mediocre level of service.

There is a great number of different factors that contribute to what is referred to in a generic way as level of service. For example, this can include occupancy density, waiting and processing times, clarity and understandability of traffic flows, itinerary lengths, and facilities to aid traffic flow. For the specific case of terminals, the amount of seating provided in waiting areas, the availability of luggage trolleys, the amount and cleanliness of toilet facilities, shops, accessibility for people with reduced mobility, etc. can also be included. For aircraft areas, the number and type of stands (contact stand next to the terminals with or without a jetway, remote stands requiring boarding by bus, etc.), the balance between the number of stands required and the actual amount provided, availability of refuelling trucks, etc. contribute to the level of service.

What often makes it difficult to quantify the level of service is that these factors are modulated by the users' perception which differs depending on thinking and behaviour patterns. The expectations of passengers are indeed very different depending on their profile (a business class passenger flying with a large national airline will have a higher level of requirements than an economy class passenger flying with a low-cost airline) or the reason for travelling (a passenger travelling for business will be less willing to wait than a passenger travelling for leisure). In much the same way, all airlines will not have the same expectations regarding the service provided to their passengers or their requirements in terms of punctuality.

The concept of level of service is simpler and better defined for terminals than for aircraft movement areas. There are indeed standards established to define and measure it in the terminals where two quantifiable criteria and objectives have emerged to assess it:

- the waiting time at the compulsory passage points;
- the space available for passing through waiting and movement areas (in a broader sense, a shopping area close to departure lounges being considered as an available waiting area).

Assessment of the level of service from these two elements alone is clearly somewhat simplistic. However, as other parameters influencing the level of service are difficult to quantity, they make it possible to measure and compare the infrastructures in a relatively simple way.

Where aircraft movement are concerned, the concept of level of service is much less standardised. Nevertheless, certain measurable parameters can be used to evaluate it. Further in this section, we will look into the issue of level of service at aircraft level.

2.1. Level of service in terminals

As mentioned above, level of service assessments in terminals are now standardised by means of a recognised method defined by the IATA *(International Air Transportation Association)* in its ADRM *(Airport Development Reference Manual)*. Revised in the 2014 edition, the categorization of level of service classes allows for a better factoring in of economic and environmental concerns related to the over-sizing of infrastructures.

Three levels of service classes have thus been defined:

- ***OPTIMUM***: enough space to accommodate the necessary functions in a comfortable environment and acceptable processing waiting times;
- ***SUB-OPTIMUM***: crowded and uncomfortable space and unacceptable processing waiting times;
- ***OVERDESIGN***: empty or too much space and over-abundance of resources.

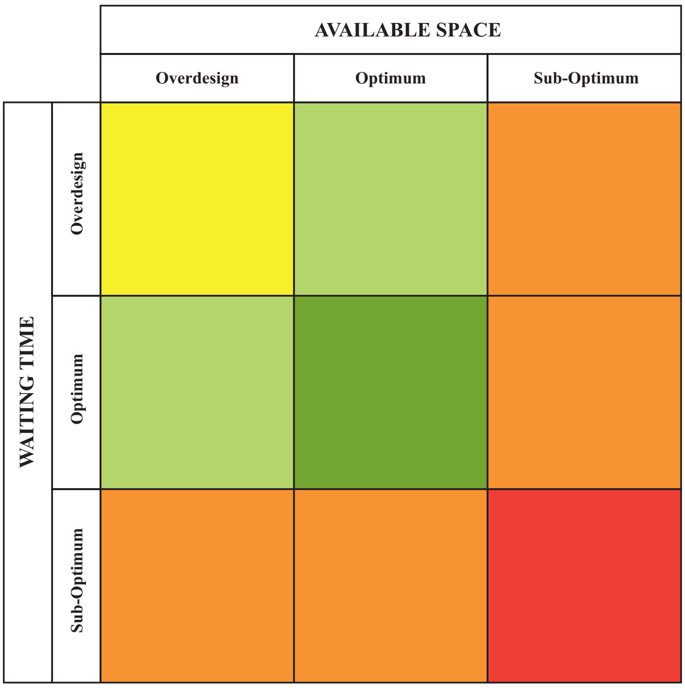


Figure 2: Space-time matrix for evaluating of the level of service in a terminal

The main development in this 2014 definition therefore comes from the introduction of the concept of terminal overdesign. It introduces an economic context that did not exist previously and which takes into account all aspects of balance between supply and demand :

- if the supply corresponds to the demand, the level of service is considered to be good;
- if the supply is less than the demand, the level of service is considered to be unsatisfactory;
- if the supply is higher than the demand, the level of service is also considered to be unsatisfactory, even though the passenger experience is good. However, this situation is still preferable to the under-sizing of infrastructure.

It is nevertheless important to note that it is generally inevitable for an airport not to be overdesigned for a specific period of time. Given the costs and time required to implement new infrastructures, dimensioning is generally carried out in a proactive way over a relatively long time scale and using long-term traffic forecasts in order to avoid having to react to a situation where installations are saturated. A new infrastructure can thus be used only in part for a defined period of time before being operated at its full potential.

The table above based on the concepts described in the ADRM shows the level of service in a space-time matrix by cross-referencing information linked to the waiting time and the available space for passengers.

2.2. Level of service at aircraft level

Unlike level of service in terminals, there is no global standard for level of service at aircraft level. Nevertheless, there are certain measurable values which make its quantification possible:

- taxiing time;
- waiting time at runway entry;
- delays.

However, the very definition of these values turns out to be complex, which makes measurements difficult to carry out. If we take the example of the taxiing time on departure, the start of the measurement could be set:

- at off-block time (and therefore including push-back time);
- at the start of the taxiing phase (and therefore not taking into account the push-back phase).

In the same way, the end of the measurement could be:

- on entering the queue for take-off (raising the issue of identifying the queue entry point, e.g. should the aircraft be stopped or taxiing below a certain speed to be defined);
- on entering the runway protection areas (and therefore including the waiting time before entering the runway in the taxiing time but not the possible waiting time on the runway);
- after line-up on the runway;
- at the start of the take-off run (raising the question of the identification of the start of take-off, as the aircraft may not come to a complete stop between the line-up phase and its acceleration for take-off).

In the same way, delays may represent various values depending on where the measurement is carried out. This could correspond to:

- an off-block time delay, i.e. the difference between the estimated off-block time (EOBT) and the actual off-block time (AOBT);
- a take-off delay, i.e. the difference between the estimated take-off time (ETOT) and the actual take-off time (ATOT);
- a landing delay, i.e. the difference between the estimated landing time (ELDT) and the actual landing time (ALDT);
- an in-block time delay, i.e. the difference between the actual in-block time (AIBT) and the estimated in-block time (EIBT);
- an increase in the journey time observed between two markers compared to a theoretical optimum journey time between these two markers.

We can therefore note that through these different definitions and methods for calculating delays, the same aircraft may or may not be delayed depending on these different options. For example, if an aircraft leaves the block late, is delayed in the queue to enter the runway but arrives at its destination at the scheduled time anyway, is it delayed or on time?

Delays are the element generally used to quantify the level of service associated with a capacity value. While there are no universal and unique definitions of delays, they are still relatively simple to measure and constitute an objective assessment of the level of saturation of an infrastructure.

3. Factors influencing airport capacity

Infrastructure capacity is influenced by a great number of parameters. It is the synthesis of many factors of different kinds (equipment, operating procedures, human factors, etc.) which influence it more or less directly.

Calculation of the capacity of an infrastructure is generally carried out based on a rather small number of parameters, such as runway occupancy time, minimal separations or the time it takes to pass through border controls in terminals. These basic parameters can be measured or deduced from a certain number of direct influencing factors (such as the geometric configuration of the infrastructure or the operating procedures in place). These direct influencing factors are themselves affected by other factors with more or less significant levels of influence, such as the terrain or the urban development surrounding an airport, which may have an influence on its operating procedures or even its geometry.

3.1. Direct influencing factors

Influencing factors can be grouped into three categoriess:

- The infrastructure – Where?
- The traffic – What?
- The procedures – How?

In the next part of this section we will look at each of these categories in more detail.

3.1.1. Infrastructure

Factors related to infrastructure have the most easily understandable influence on the capacity of the system. They correspond to:

- **the geometry** of elements (and by extension their maximum possible level of performance);
- **the condition** of elements (and by extension their instant level of performance, which may be impaired as a result of contamination or external disruption);
- **their configuration**, i.e. their mode of operation such as the runways' operation direction, or the distribution of check-in desks amongst different airlines (it is not possible to obtain maximum performance of an element in all conditions);
- **their quantity.**

At this point, it is necessary to understand the links between these different concepts. It is generally required to act on several of them at the same time to be able to improve the overall performance of the system. For example, increasing the quantity of elements will not always make it possible to increase the level of performance if the geometry of these elements is not favourable. Indeed, adding a second runway is not necessarily synonymous with doubling the capacity if the two runways cannot be operated independently (for example with intersecting runways or parallel runways that are too close to one another).

At aircraft level, these elements correspond to the elements listed below:

- stands and their type (contact or remote, connected via a jetway or not, the number of stands, the ability to use them at the same time, etc.);
- runways (their quantity, the option to use them at the same time, state of contamination, etc.);

- runway entries for take-off;
- runway exits;
- taxiways connecting the runways and the stands;
- air traffic approach sectors which are found at the interface between airspace and the infrastructure on the ground.

For terminals, these correspond to the following elements:

- check-in desks: their quantity, their configuration (dedicated to airlines or generic);
- security screening;
- border control and customs control;
- departure lounges and gates;
- walking areas between checkpoints;
- waiting areas, including commercial areas (restaurants, shops).

All these elements of infrastructures directly influence the parameters that make it possible to define the capacity of the system.

3.1.2. Traffic

To continue on with the systemic definition provided at the beginning of this guide, traffic corresponds to the flow that flows through the links, processors and reservoirs. Even though the impact of traffic on the performance of the system is much less obvious than that of the infrastructure, it is all but negligible. The characteristics of the traffic in terms of mix and proportion directly influence the capacity of the airport in its entirety. For example, the presence of Mobility Impaired Persons (MIP) in terminals will have a direct influence on the flows in movement areas (they generally take up more space and move at a reduced speed), as well as checkpoints. However, if there is a low proportion of MIP, the impact on the flow will only be occasional (i.e. only when MIP are present) and will therefore be almost negligible over a much longer time scale.

At aircraft level these factors correspond to:

- the types of aircraft (category of wake turbulence for runway separations, and category of wingspan for stands, or category of performance for other factors such as runway occupancy constraints);
- the proportion of aircraft of each type in the global fleet;
- the share of traffic between departures and arrivals.

For terminals, they correspond to:

- the mix of passengers ("frequent flyer" passengers, MIP, passengers in groups);
- the origin or destination of passengers (domestic or international passengers require different controls);
- the mix of flights (normal, charter or low-cost) which has an impact on the amount of baggage per passenger (cabin or hold baggage) for example;
- the distribution of passengers between departure, arrival or transit passengers;
- the reporting profile of departure passengers in the terminal (i.e. the time distribution of arrival at the airport and at different passage points).

In much the same way as the factors linked to the infrastructure, they have a direct influence on the basic parameters for calculating capacity.

WAKE TURBULENCE

Wake turbulence is the main reason for imposing separations between aircraft in approach airspace areas and at the runways. All aircraft in flight generate wake turbulence, which essentially takes the form of two vortices. The risk to the aircraft crossing the wake turbulence of another aircraft is all the more significant as the aircraft that generates the wake turbulence is large and the aircraft that is subjected to it is small.

This physical phenomenon of fluid mechanics is explained by the difference in pressure between the underside and the topside of the wings which makes it possible to generate lift. At each wing tip, the high-pressure air below the wing rolls up to the low-pressure area above the wing to form a vortex.

For passenger airliners, the formation of the vortex occurs behind the aircraft within a distance of approximately 10 times the wing span of the aircraft. The vortex generally lasts for a few minutes while gradually sinking under the path of the aircraft. It is thus possible to encounter the wake turbulence up to 10 NM behind a passenger airliner and less than 1,000 feet below its path. The vortices remain concentrated in a very tight volume (less than 2 wingspans wide) and maintain their energy until they decay.

In the vicinity of airports, the interactions with the ground, in particular rebounds, make their paths difficult to predict.

For more information on the subject, please refer to the Technical Information Note (available in French only) on LIBELaéro (La Turbulence de Sillage, April 2016).

3.1.3. Procedures

The last category of direct influencing factors relates to operational procedures, i.e. all the rules that define the way in which entities (passengers or aircraft) interact both with their environment as well as with each other. The entire airport process is highly regulated for security and safety reasons, and the majority of the interactions that can be observed are defined by procedures which define the behaviours of entities within the system. These constraints are particularly visible at aircraft level, where the entire process (from the departure gate to the arrival gate) is just as well defined on the side of air traffic control and the operator as on the side of the aircraft crews within airlines; whereas on the side of terminals, a much greater freedom is left with passengers, although they do have a certain amount of obligatory tasks to carry out, which makes them the subject of specific procedures themselves.

It is important to note that these procedures can be formal rules (i.e. written rules – regulatory texts, operating manuals) or local operational practices (habits and customs connected to the usual practices and expertise of the local actors).

In terms of aircraft, these regulatory procedures regulate in particular the way in which the aircraft are separated from each other to avoid the risk of collisions or of encountering wake turbulences from other aircraft.

By definition, local operating practices are much more varied as they stem from very specific local criteria as well as from the local staff present. These often involve tactical decisions (i.e. in very short time scales) that allow for the optimization of the operations at a given time. These are empirical practices, which often arise from the experience of the local staff. For this reason, when carrying out an analysis of the capacity of a system it is essential to spend time with operators to understand their operational practices beyond the regulatory context. This requirement is all the more necessary as the analysis is performed using simulations (see chapter 4) where a reliable and detailed reproduction of the behaviour of entities is required.

3.2. Indirect influencing factors

Unlike the direct influencing factors, the factors presented in this section do not need to be analysed within the scope of the capacity assessment of a given airport system. However, it is important to mention them as from an airport infrastructure planning standpoint, understanding the effects that they could indirectly have on issues linked to air traffic circulation often makes it possible to anticipate future needs and to direct the development of infrastructures in a more optimum way than by simply reacting to the demand changes.

There are different sorts of indirect influencing factors and they fall into the following categories :

- the economic and strategic context,
- the environment (in a broad sense),
- the regulatory framework,
- technological development,
- human factors.

In this section we will go over these different categories and explain them.

3.2.1. Economic and strategic context

The national and international context has a huge impact on the volume of passenger and freight exchanges, i.e. on the traffic demand. The impact of the economic context was particularly visible in recent major crisis (the 2008 financial crisis, the terrorist attacks of September 11, 2001) where it was possible to observe reductions in traffic in the affected areas as well as notable changes to the traffic mix aiming to optimise costs (increase of aircraft occupancy and size, i.e. the number of passengers per aircraft).

In conjunction with the global economic context, the local context also has an impact. The characteristics of the local economic activity influence the type of traffic. The strong presence of businesses will introduce significant business traffic and will require connections to large hubs nearby, or even the creation of a hub locally. A high level of tourism will lead to significant charter traffic from tour operators as well as the presence of low-cost airlines. This will have an impact on the aircraft used and the organisation of flights (from the point of view of schedules).

The strategic context corresponds both to that of the airlines and that of the airports.
On the airport's side, strategy is expressed by different levers:

- The choice of investment types selected and the amount that is allocated to them. They directly influence the infrastructure and therefore its capacity.
- The pricing policy that allows them to attract specific types of traffic (low-cost airlines, business aviation), with an impact on the types of aircraft and passengers and on the distribution of traffic throughout the day.
- The level of service and services provided to passengers; to maximise the use of its resources, an operator may make the choice to "degrade" its level of service (which is usually expressed by longer delays and less comfort for passengers). It may also offer specific services to attract certain types of passengers, for example by providing lounges for high-yield passengers.
- Operational management of resources, which can vary from one airport to another, for example in terms of gate allocation, or in terms of provision of resources during peak times.

These parameters are clearly often interconnected with each other. For example, attracting high-yield passengers may require both specific investment and a high level of service.

As for the airlines, they look to focus their efforts on their markets in terms of passenger profiles and network's destinations. In this regard, they choose their aircraft based on economic criteria (acquisition, running and maintenance costs) and offer their products (frequency, on-board services, services on the ground, etc.) to best satisfy their customers. This strategy is reflected in a specific type of offer for each airline, allowing them to differentiate themselves for the passengers.

The strategies of both entities (airlines and airports) are closely linked, with one directly influencing the other and vice versa. The change in an airport's pricing policy may lead to the settling in or the withdrawal of certain airlines with particular characteristics. Conversely, an airline that wishes to base itself in a specific infrastructure may cause the airport to make changes to their strategy if the economic stake of accommodating this airline is high enough.

3.2.2. Environmental factors

As mentioned at the start of this chapter, environmental factors correspond to the environment in which the airport is located. This relates to the meteorology of the area and the local topography as well as to the urban context in which the airport is situated. While these factors may have an indirect influence on capacity, their impact is particularly significant on the general operation of the system.

Meteorology has an influence at aircraft level (as well as on airport access, but this is not covered in this guide), as it can lead to significant changes to basic parameters used in the evaluation of capacity:

- Separations to be applied between the aircraft may be significantly increased when visibility is poor, or if a particular weather event is occurring close to the airport (storm, high winds). In some cases, adverse meteorological conditions can lead to the complete closure of the platform, leading to significant delays and flight cancellations.
- The contamination of the infrastructure (its condition) by rain, snow or ice may lead to an increase in landing distances and therefore change the constraints relating to runway occupancy, which will require additional precautions on separations between aircraft to limit the rate of missed approaches. A missed approach results in the loss of a movement on the runway and makes it necessary to insert the aircraft having gone around in the arrival sequence again.

The impact of meteorological conditions on the capacity of a system is usually limited to a certain period of time. This may be an event lasting a few minutes (storm), several hours (wind) or may be seasonal (snow and icy conditions). When a meteorological event becomes frequent and recurrent, the operator of the infrastructure will usually put in place measures to allow them to maintain as high a level of performance as possible during the event. For example, this is the case for northern European airports where significant measures are implemented during the winter season to maintain the accessibility and the performance of the infrastructures.

In contrast, the local topography and urbanisation are elements that do not change much over time and they must be adapted to permanently. They have an impact on:

- Procedures: due to topography, certain specific procedures may be put into place. These are generally more restrictive than "standard" procedures.
- Infrastructures; the presence of restricting natural elements (mountains, sea) may limit the expansion of infrastructures and slow the development of installations and overall activity.

NICE CÔTE D'AZUR AIRPORT, BETWEEN MOUNTAINS, SEA AND CITY

Nice Côte d'Azur airport, the largest airport in France after the Paris airports in terms of passenger traffic (over 12.4 million passengers in 2016), is located in a particularly restrictive local environment.

First of all, the presence of mountains, with peaks reaching over 10,000 feet to the north of the airport result in a significant asymmetry of the terminal movement area, with a substantial concentration of procedures on the southern half of the area over the sea. In particular, when the airport is operated in configuration 22 (i.e. when landings and take-offs take place towards the south west), a direct approach is not possible due to the terrain, and this leads to airport accessibility issues when this configuration is combined with low visibility. In this case, the only instrument approach available for aircraft ends in a visual manoeuvre which is not possible if the visibility is insufficient.

The sea is obviously present around the airport as it is built on land reclaimed from the Mediterranean. This configuration represents a clear impediment to further development of the infrastructure given the costs that expansion over the sea would involve. The airport must therefore do with its existing land area for future developments.

Finally, it should be noted that the airport is located within a particularly dense urban fabric. From the infrastructures' standpoint, while the sea limits expansion to the south, it is the city that limits expansion to the north. From an operational viewpoint, several specific procedures are put in place in order to limit the negative impact of operations on the population, such as the instrument approach in configuration 04 which makes it possible to avoid flying over the Cap d'Antibes.

3.2.3. Regulatory framework

The regulatory framework influences almost all other influencing factors. As mentioned in section 1.4, the regulator may have a direct influence on capacity by means of mechanisms to limit traffic (night-time curfews, limitation of the number of annual movements, etc.) for environmental reasons, usually in dense urban areas.

Given the international nature of air transport, the regulatory framework usually extends beyond the borders of the country where the airport is located. At an international level, the ICAO (International Civil Aviation Organization) develops standards and recommendations that are then adapted into the national regulations by each Member State. In certain parts of the world, intergovernmental agencies make it possible to standardise regulations amongst affiliated countries. This is for example the case within the European Union with the EASA (European Aviation Safety Agency).

The regulatory framework represents two main aspects:

- On the one hand, the development of the standards that have an influence on infrastructure planning and the operating procedures design. For example, these are defined by:
  - the minimum spacings between the different elements of the infrastructure (taxiways, runways, stands);
  - the type of equipment required to ensure operational conformity (security screening points, border controls, air navigation systems);
  - minimum separations between aircraft in flight.

  This aspect of the regulatory context has an impact on infrastructure and the parameters that directly influence capacity.
- On the other hand, questions relating to economic regulation of air traffic, which have an impact in particular on:
  - the pricing of aeronautical taxes and fees owed to state services;
  - policies for improving access to remote areas through public service obligations leading to the creation and continuation of certain routes;
  - coordination procedures already mentioned previously.

This aspect of the regulatory framework has an impact on the traffic, i.e. on the one hand the type and quantity of the transport services provided for users and on the other the demand in terms of number of movements and passengers in different airports.

3.2.4. Technological framework

The technological framework is also a factor that affects several parameters that have a direct influence on capacity. It plays on two main aspects:

- On the one hand, the characteristics of traffic flows using the infrastructures. For example, these correspond to:
  - the improvement of on-board systems in the aircraft that make it possible to put in place new, improved air navigation procedures;

  - the modification of physical characteristics of aircraft making it possible to increase the average seat capacity; although this is also accompanied by an increase in space taken up on the ground or wake turbulence constraints;
  - systematic use of online services for checking in passengers.
- On the other hand, the improvement of systems for processing air traffic, such as:
  - new measures making it possible to strengthen passenger screening in terminals and changing their processing time;
  - new systems for managing aircraft movements that optimise the processing of aircraft;
  - the development of new navaids such as satellite positioning which makes it possible to establish new procedures that were not possible with conventional navaids.

3.2.5. Human factors

Human factors represent an influencing factor that can't be ignored, and one that presents the dual issue of being difficult to quantify while also requiring a long time to analyse.

They correspond to everything relating to human behaviour and will depend on staff training, tiredness, stress caused by particular situations or even the operating instructions that they have been provided with. These are human factors that, among others, contribute to the differentiation of the notions of maximal capacity, operational capacity and sustainable capacity.

They also introduce risks and uncertainty into the system (for example processing times or reaction times to instructions) which necessitate the use of operational margins to ensure its robustness and resilience.

They therefore have a direct impact on the efficiency of operations and the overall capacity of the system. Human factors are obviously not specific to aircraft or terminal operations, since while they are assisted by many systems, humans are still at the core of the processes both on the terminal side and the aircraft airside of an airport.

Let's take the example of pilots to illustrate these concepts. They influence the level of capacity through:

- their reaction time to clearances given by air traffic control, in particular regarding line-up and take-off on the runway, where responsiveness to instructions is particularly important;
- training and experience: detailed knowledge of the aircraft makes it possible to adjust the braking management to use runway exits that minimise the constraints of occupancy of the runway on arrival;
- knowledge of the infrastructure: this allows pilots to anticipate the manoeuvres they will need to carry out and therefore be more reactive to instructions. Good knowledge of the airport is seen particularly in pilots whose airline is based at the airport and who are therefore used to flying there on a very regular basis.

3.3. Basic parameters for calculating capacity

From these aforementioned factors it is possible to derive a certain number of parameters used in the methods for assessing the capacity of an infrastructure. These methods will be described in more detail in the following section.

3.3.1. At aircraft level

In the case of capacity at aircraft level, a limited number of basic parameters can be used to assess the performance of an infrastructure. In particular, these correspond to:

- time separations on the runway between two successive movements (two departures, two arrivals or a departure and an arrival);
- runway occupancy constraints (runway occupancy times or ROT, i.e. the time during which the runway system is unavailable to another aircraft);
- sequencing of aircraft on the runway;
- aircraft turnaround time (which is used more specifically to evaluate parking capacity).

These parameters are determined by the physical characteristics of the infrastructure, the traffic mix and by the operating procedures in place. For example, time separations will depend on the aircraft wake turbulence categories and the constraints linked to the geometry of the infrastructure; and aircraft ground handling times will depend on their airline's strategies and aircraft sizes.

Using capacity assessment tools, these parameters make it possible to carry out the calculation. We will come back to the calculation in more detail in chapter 4, which deals with determining airport capacity.

The diagram below summarizes the main elements discussed here and their influence on the capacity of a system at aircraft level.

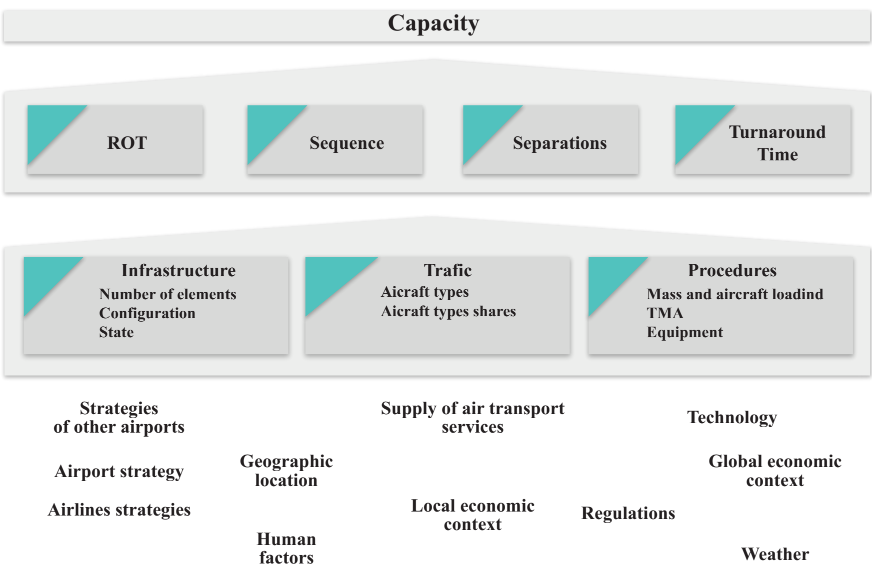


Figure 3 : Diagram of parameters influencing capacity at aircraft level

3.3.2. At terminal level

In the case of capacity at terminal level, the quantity of data to take into account for the assessment is slightly higher than at aircraft level, due on one hand to the lower level of consistency among processes and entities flowing through the system, and on the other hand to the greater dispersion of passengers in terminals. Passengers all have their own characteristics with a certain number of «tasks" to carry out. They must thus (depending on whether they are arriving or leaving):

- check in ;
- go through security screening;
- go through border controls;
- board/disembark;
- go through customs;
- collect their baggage.

Furthermore, not all passengers necessarily have to carry out all of these formalities. This is for example the case for transit passengers, those who arrive at departures without hold baggage (and therefore don't have to check these in), or passengers arriving from and to a domestic airport who do not need to pass through border controls or customs, etc. Due to this heterogeneity of passenger profiles, the quantity of required data is therefore significant.

The parameters for calculating the performance of a system at terminal level are as follows:

- Processing times at different steps;
- The strategy allocating resources depending on the characteristics of the passengers;
- The space available to place resources and their respective waiting areas;
- The intended level of service, expressed as a ratio of density of passengers and maximum waiting time at checkpoints.

The characteristics of passengers (i.e. the traffic mix) will directly influence these different parameters. Therefore, it is also necessary to gather additional data on the characteristics, such as the proportion of passengers with hold baggage (which itself depends on the strategy of the local airlines), the proportion of passengers who check in online or the average number of meeters and farewellers per passenger (related to the issue of public spaces).

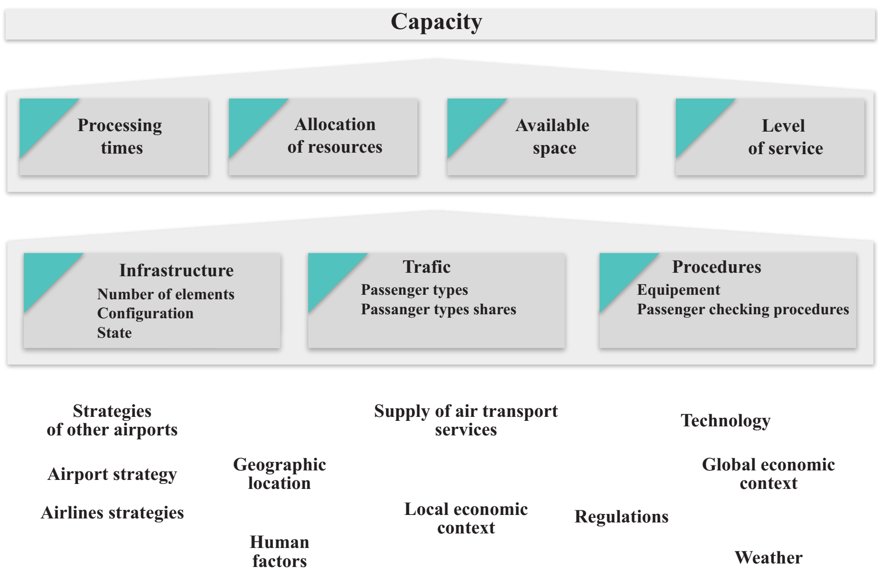


Figure 4 : Diagram of parameters influencing the capacity at terminal level

4. Evaluation of infrastructure capacity

When assessing the capacity of an infrastructure, it is necessary to ask a certain number of questions at the very start of the process in order to anticipate as early as possible the requirements for its proper implementation in terms of both material and human resources. These questions are:

- *Why?* – Depending on the aim of the analysis, it will not always be necessary to go into a very high level of detail. Therefore, it may not be necessary to use complex simulation tools or to acquire a large quantity of data for the implementation of the analysis. The intended aim is also important when determining the indicators to be produced during the analysis in order to present the results in the best way.
- *When?* – The time required to implement certain types of tools varies. Therefore, it is necessary to plan the start of analyses accordingly.
- *How?* – Preparing a suitable methodology is important to assess the resources required to carry out the analysis, and this is required for the whole of the process (from the data collection to the production and analysis of the results).
- *Who?* – While some types of analysis do not require specific expertise in the field of capacity, the use of certain tools and in particular simulation software require experienced users if the tools are to be utilized properly and effectively.

In this section, we will present the whole of the process by following its logical flow.

4.1. Needs and types of analysis

While capacity analyses often aim at evaluating the performance of an infrastructure within the scope of infrastructure planning or coordination issues, it is simplistic only to consider these cases.

Using the definitions provided in chapter 1, we have seen that capacity can correspond to various concepts, each of which having their own benefits for the different actors involved with an airport platform. Therefore, it is possible to define three categories of analysis type, each of which being associated with a different concept of capacity:

- **Structural analyses** that correspond to analyses on a macroscopic level in the medium-long term and consist of maximal capacity measurements for planning purposes. In this type of analysis, the most important aspect relates to the hypotheses that are made, in particular the long-term traffic forecasts.
- **Programming analyses** which on a much shorter time scale aim to assess the quantity of traffic that could be processed for the coming aeronautical seasons by an existing infrastructure. This generally involves determining the sustainable capacity of the infrastructure to ensure a good balance between supply and demand, and to be able to anticipate possible difficulties both on the ground and in the air.
- **Operational analyses** that focus on short-term operational management issues. These involve determining the operational capacity. The aim is to include constraints that appear in the very short term in this type of analysis in order to obtain the "immediate" level of performance of the infrastructure. This makes it possible to update the level of performance of infrastructures and to anticipate the operational management measures which need to be put in place.

It should be noted that the capacity of an infrastructure may vary significantly depending on the operating conditions. It may be useful for the operator to know their level of performance in adverse conditions, in particular if these conditions occur recurrently (specific meteorological conditions, unavailability of certain infrastructures, etc.). The three types of analysis described above may therefore be adapted to different conditions.

4.2. General methodology

No matter what question is being asked, and whether it concerns passengers or aircraft, it is possible to adapt a common general methodology to any specific evaluation of the capacity of an airport infrastructure. Once the scope has been perfectly defined (i.e. once the response to the previously described "Why?" question has been provided), it is first necessary to be able to determine which tools will be used to carry out the analysis. The tools will indeed influence the quantity of data required to carry out the assessment, the mix of indicators that can be produced and the type of scenarios that can be considered.

Once this preliminary step relating to the choice of tool(s) has been completed, the generic process is as follows:

- *Identification of the required data*: as mentioned above, the type and quantity of data required for the analysis depends on the type of tools used, as well as other factors such as the level of detail of the analysis and the desired level of accuracy for the results and the conclusions.
- *Production of data*: once the needed data has been identified, it makes sense to proceed with its production as soon as possible, as some data may require a long time to be acquired. For example, this is the case for data requiring field surveys to be carried out. In certain cases, the time taken to produce the data may significantly affect the planning of the analysis.
- *Developing the analysis scenarios*: this phase can be carried out at the same time as the phase of data production, if it is required (i.e. if the objective is to assess the performance of an infrastructure in future conditions, which is the case for medium or long-term analyses). The scenarios usually involve changing one or more elements, such as traffic (quantity and/or mix), the infrastructure (addition or removal of elements, reconfiguring certain areas) or the operating rules of the system or of some of its sub-systems.
- *Definition of relevant indicators*: before proceeding with the modelling phase, it is essential that the indicators that will be used to present the results of the analysis are defined. The capacity assessment of an infrastructure is not always about assessing the raw quantity of traffic that can be processed (in passengers per hour or movements per hour). More and more, it is necessary to produce indicators that highlight other issues, such as environmental or safety issues, or indicators that put more emphasis on the level of saturation of an infrastructure. These considerations must be taken into account before developing the models, as they generally have a significant influence on this phase, since the models may often need to be adapted specifically to the production of one particular indicator.
- *Developing the models*: regardless of the type of tool used (analytical tools, real time simulation tools or fast time simulation tools), it is necessary to develop a model corresponding to each of the defined scenarios. Their development occurs by modelling the infrastructure (by setting a certain number of relevant parameters in analytical tools, or by reproducing the infrastructure in simulation tools), as well as its operating procedures.
- *Verification, calibration and validation of models*: this is an iterative process made up of three steps. In order to ensure the proper operation of the models, it is important to carry out a first step of verification, which consists of ensuring the proper implementation of the operating rules and that there are no mathematical or programming errors in the modelling. The second step involves the calibration of the model. This involves adjusting the parameters and rules of the model to be able to reproduce a measured real situation as accurately as possible based on quantitative elements, as well as on qualitative elements in certain cases. The final step is validation, which is carried out on sample of data that is different to that used for the calibration. The quantitative indicators used in the verification, calibration and validation phases should correspond to the indicators defined previously in the methodology and

may be associated with additional qualitative elements. If necessary, the verification and calibration steps must be repeated until there is a definitive validation of the model. This phase is important as, on the one hand, it makes it possible to assess the credibility of the models and therefore the results that they will produce and, on the other hand, to measure the bias introduced by the modelling, which needs to be taken into account when interpreting the results.

• *Results production and analysis*: the final step involves producing and analysing the results based on the relevant indicators selected earlier in the process and the bias measured in the previous phase (see Figure 5 below). This step is important and requires a lot of attention, as it is at this point that the quality of the capacity assessment of the infrastructure is highlighted. In some cases, the analysis of the results may lead to changing the analysis scenarios to be able to take into account elements that were not anticipated.

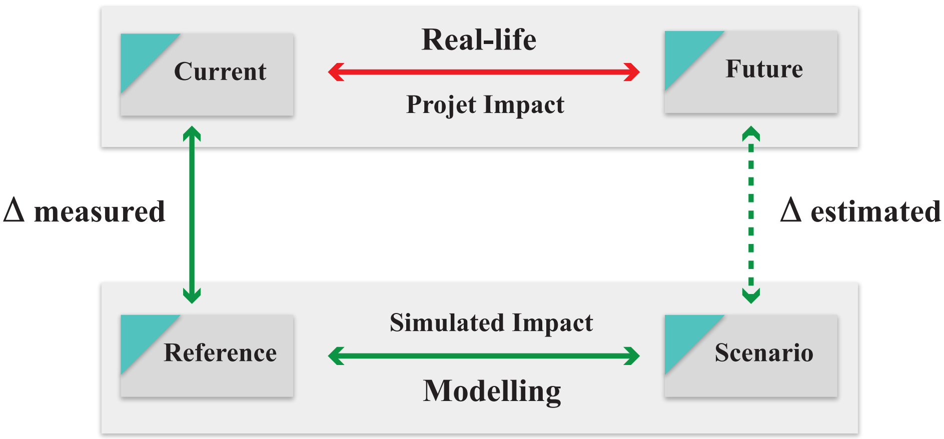


Figure 5: Evaluation diagram of a scenario using modelling

The diagram below summarises all of the different steps

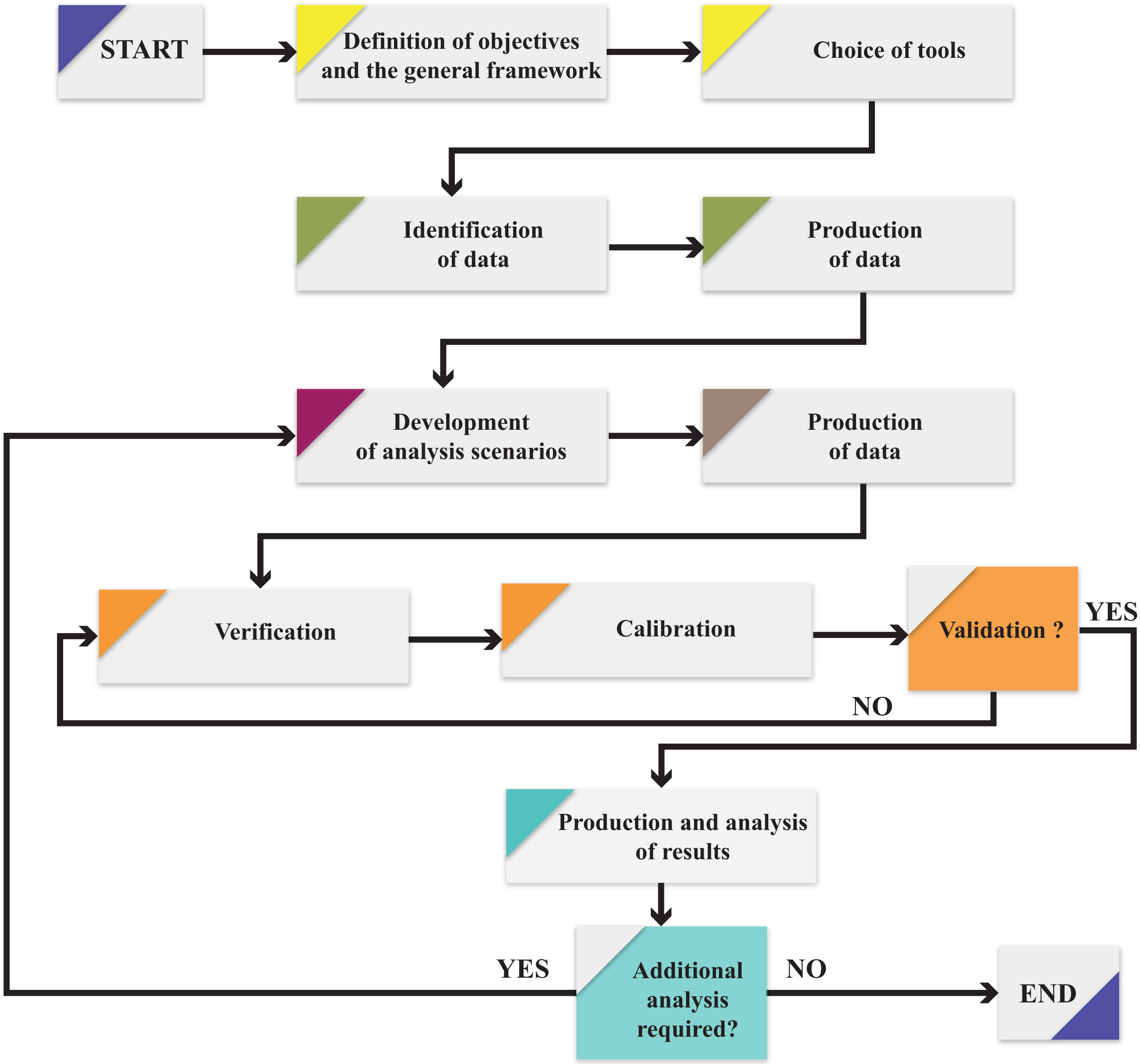


Figure 6: General methodology of an analysis to assess airport capacity

4.3. Data

The data required to assess the capacity of an airport infrastructure can be extremely varied depending on the question asked. However, three categories of data are always required (with a more or less significant level of detail):

- infrastructure data;
- traffic data;
- conditions under which the resources may be used.

The infrastructure data corresponds to the "physical" aspect of the system. For a terminal, this corresponds to the arrangement of the different terminals (concourse areas, positioning of entrances and exits, escalators, etc.) as well as the amount and availability of the different resources (check-in and information desks, security screening points, etc.). At aircraft level, this corresponds to the network of taxiways and runways, as well as stands or any other element that may be relevant for the analysis, such as de-icing areas. If runway systems are to be considered, it is necessary to consider at least the interface between the terminal manoeuvring area and the ground infrastructure (final approaches and initial climbs). This data can be obtained from blueprints provided by the operator, published aeronautical information or even from surveys carried out on site.

As already mentioned (see chapter 3 on influencing factors), traffic has a significant impact on the throughput of an infrastructure. Traffic data is relatively different depending on whether the interest is at passenger or aircraft level. In terms of terminals, on the one hand data corresponds to flights (schedules, number of passengers, origin/destination, airline, etc.) and on the other to the passenger profiles. Knowledge of this data is decisive for the capacity analysis of a terminal insofar as the formalities to be completed, the behaviour or the acceptable level of service may differ depending on the passengers. While flight data can be acquired from schedules, data regarding passenger profiles generally requires on-site surveys on a representative sample of passengers. If such surveys are impractical, hypotheses can be made based on the type of airport, the flown airline and the destination. Depending on the tools used, it may also be necessary to know at what time passengers arrive at particular points in their journey (e.g. at the entrance to the terminal). This data can be obtained from passenger reporting profiles, which can be obtained locally or by using standard profiles depending on the type of flight (business, leisure, charter, low-cost, etc.). At aircraft level, traffic data (type of aircraft, schedule) can be obtained from schedules or by using trajectories recorded by the radar systems if they are available.

When considering the capacity of an infrastructure in specific conditions, other data types such as weather data could be required.

4.4. Key Performance Indicators

The throughput in number of movements or passengers per unit of time is generally the most commonly used indicator to quantify a level of capacity. However, it is also often useful to express results with other indicators, which reveal other phenomena and in particular identify the operating conditions under which the calculated level of performance is achieved. For example:

- The average taxiing time per aircraft between the runway and the gate (for departure or arrival); this indicator may bring to light issues of congestion on aprons, taxiways or at the runway entries.
- The length of queues upstream of screening points in terminals; this data may be important in conjunction with the capacity (in number of passengers per hour) of each screening point in order to effectively provision waiting areas.
- The overall fuel consumption and pollutant emissions; today, it is increasingly important to carry out multi-criteria analyses that cover environmental issues. It is actually not uncommon for the improvement of capacity in a scenario to be achieved to the detriment of other indicators such as the overall aircraft fuel consumption.

These few indicators are of course only examples among many others as more specific indicators requirements may arise from particular types of analysis, client requests or the configuration of the infrastructure. While raw performance is often the main objective of an analysis, it is also possible the analysis could focus solely on the issue of level of service, and more generally on the conditions in which the traffic flows. In some cases, it is thus possible to aim only at improving the level of service and to use only indicators that relate to this issue, without even attempting to quantify the throughput.

4.5. Scenarios

It is often essential to consider several scenarios when carrying out a capacity analysis, in particular for structural analyses or planning analyses, which involve more distant time frames where the level of uncertainty may be significant, both in terms of infrastructure and traffic characteristics. For time frames of several years or even several decades, covering all eventualities is an exercise that requires multiple hypotheses to be taken into consideration, resulting in numerous different scenarios depending on the anticipated characteristics of the predicted infrastructure or traffic forecast.

In terms of traffic, the scenarios may correspond to several hypotheses regarding increase in demand (for example "optimistic" scenarios envisaging a significant increase in demand, and "pessimistic" scenarios envisaging a low level of increase in demand), and regarding the types of traffic (for example, scenarios predicting significant development in long-haul activity or the activity of low-cost airlines).

In terms of infrastructure, long-term issues are generally involved given the significant investments that the infrastructure represents and the amount of time required for their construction. It is not uncommon that when several new infrastructures are planned, the capital available or the constraints linked to works phasing do not allow for all of these to be completed at the same time. In addition, it is also necessary to model different combinations of new infrastructures and different phases of their realisation in order to assess the performance of the system in different possible configurations. Along with new infrastructures, the same issues may emerge in the case of more short-term works, with several scenarios of unavailability of some parts of the infrastructure and new operation plans for the infrastructures that remain operational.

4.6. Analytical and simulation tools

There are two main families of tools for analysing airport capacity. Analytical tools on the one hand, and simulation tools on the other (in real time or fast time). These two tool families each have their advantages and drawbacks in terms of scope, implementation time or accuracy of their results. In this section we will look at the two categories of tools in detail.

4.6.1. Analytical tools

Analytical tools implement a succession of mathematical formulae to obtain the capacity of an infrastructure based on a limited number of parameters. They are generally simple and quick to implement once all of the data has been acquired. The results provided by this type of tool provide a good overview at a macroscopic level of the performance of an infrastructure and are therefore particularly useful if the aim is to quickly obtain an estimate of the capacity of a system. However, as these are the result of mathematical formulae, they can only consist of quantitative indicators that were predefined during the construction of the tool.

These tools are generally created to respond to an issue limited to a particular sub-system. This limitation makes it possible to simplify problems enough so that they can be resolved using one or more mathematical formulae. There are thus tools that deal specifically with the question of airport terminal capacity, others that focus on runways, or on parking areas. Specific mathematical models for each of these areas make it possible to assess their performance.

However, these tools often have a limited scope of application as, by nature, they cannot respond to questions for which they were not designed. This means that when departing from the scope of the "classic" analysis, or whenever the studied infrastructures have atypical characteristics (either regarding the infrastructure itself or its operation) it is not always possible to use this type of tool.

For terminals, the analytical tools consist of a successive application of ratios and simple formulae in order to determine the capacity of each of the components (i.e. the waiting areas, movement areas and processing areas), then the overall capacity of the terminal is deduced from the capacity of the components. To implement this method, it is necessary to know the available space in the terminal for each of the movement and waiting areas, as well as the aggregate data on the mix of passengers and processing times at different passage points. Finally, the maximum waiting times at each processor, as well as the ratios adapted to the intended level of service must be selected in order to determine the space required per passenger in the different areas (to achieve a higher level of service, it is necessary to provide more space per passenger to increase their perceived comfort). For check-in, for example, the calculation is made in the following way:

- For check-in desks:

$$C_{desks} = N_{dom}\,\frac{3600}{T_{dom}} + N_{int}\,\frac{3600}{T_{int}}$$

Where :

- N_{dom} et N_{int} correspond to the number of domestic check-in desks and the number of international check-in desks respectively;
- T_{dom} et T_{int} correspond to the average time (in seconds) taken to process domestic and international passengers respectively;
- C_{desks} corresponds to the capacity of check-in desks in passengers per hour.

- For waiting areas:

$$C_{desk\ wait.} = \frac{S}{R} \times \frac{60}{T_{desk\ wait}}$$

Where:

- S corresponds to the total waiting area space;
- R corresponds to the ratio of space allocation per passenger to be defined depending on the anticipated level of service;
- $T_{desk\ wait.}$ corresponds to the maximum waiting time (in minutes) at check-in to be defined;
- $T_{desk.wait.}$ corresponds to the capacity of the waiting area at check-in in passengers per hour.

For runway systems, the calculation is generally made in two steps. The first consists of determining the minimum separations between each pair of aircraft (depending on the number of categories of aircraft defined by the user) and for each type of sequence (arrival-arrival, departure-departure, departure-arrival, arrival-departure) based on the geometric characteristics of the infrastructure and the local operating conditions which are reflected by a limited number of parameters. The second step involves determining the probability of encountering each pair of aircraft (leading aircraft/following aircraft) and the type of movements depending on the selected traffic mix. By correlating the basic separations and the probability of encountering a pair of aircraft, the tool is able to determine the capacity of the system. The formula to determine hourly capacity is as follows:

$$C_{RWY} = \frac{3600}{\Sigma_{i,j}\, p_{ij} s_{ij}}$$

Where :

- p_{ij} represents the probability of encountering a pair;
- s_{ij} represents the time separation (in seconds) required between the movements i and j;
- C_{RWY} is the capacity in movements per hour of the runway.

This method provides an approximation of the maximal capacity of an infrastructure.

For the capacity of aprons, the standard analytical methods are those developed by Horonjeff[3]. The most basic method consists of determining the capacity of airport parking areas in an aggregated way, without taking into account operating restrictions linked to the size of the aircraft or the allocation scheme. Capacity is expressed as follows:

$$C_{APRON} \leq \frac{u \text{ x } N}{\Sigma_i\, p_i T_i}$$

Where:

- N represents the total number of stands available;
- u is a coefficient of use of the stands between 0 and 1; a value of 0.8 indicating that the gate is occupied 80% of the time, for example;
- $\sum_i p_i\, T_i$ represents the weighted average occupancy time of the stands (p_i corresponds to the proportion of category i aircraft, and T_i corresponds to the average occupancy time of the stands for category i aircraft).

This method only gives an estimate of the capacity of an apron. A variation of the same method makes it possible to refine the calculation in order to take into account usage restrictions of stands to certain types of aircraft only.

While tools generally exist to respond to generic issues, it is not uncommon to have to develop specific tools to address specific issues. The relative simplicity of some solutions from both a mathematical and an IT implementation standpoint makes it possible to consider developing solutions tailored for specific requirements.

[3] ***Planning and Design of Airport, Fifth Edition***

4.6.2. Fast time simulation

4.6.2.1. Scope of application and benefits

Unlike analytical tools, rather than mathematically modelling the operation of a system, simulation involves reproducing the operations by modelling individually the behaviour of the entities. The aim is to create a reproduction of the real system in the simulator in order to conduct the required analyses. The term "reproduction" does not mean that it is an exact replica of the real system. In fact, it is necessary to make a number of hypotheses during the modelling process in order to implement the behaviour of the entities using simplified rules. The following definition summarises all of these points: a simulation model is a virtual, simplified replica (the level of simplification depends on the hypotheses made) of a real system and it must reflect with adequate accuracy all the properties of the real system which are deemed relevant with regard to the aim(s) of the analysis.

Analytical tools have a limited scope of action and the implementation of fast time simulation tools (i.e. where time passes more quickly than in reality, as opposed to real time simulation tools) is generally appropriate when analysing complex systems (whether from an infrastructure or an operating rules standpoint), when the required indicators cannot be produced using analytical tools, or when a higher level of detail and precision is required.

The development of a model in a fast time simulation tool consists of a first step of infrastructure modelling (i.e. reproduction on a physical level), then a second step of operational rules implementation which allows to reproduce the operating conditions of the infrastructure.

These tools provide the benefit of being able to visualise the produced simulations. This is an important element at different steps of the analysis process:

- First, in the development phase of the models, the visualisation makes it possible for the modeller to quickly detect the presence of operational modelling errors (poor passenger or aircraft flow, abnormal points of conflict, too high waiting or processing times, etc.) without having to analyse and interpret the indicators. It is thus possible to identify quickly all errors in the input data or in the model settings that have an impact on how operations progress.
- Then, during the calibration and validation phase, the visualisation of simulations helps discuss the modelling more efficiently and directly with the people in charge of the operations on site. This qualitative validation is important as, in addition to the improvements of the model it leads to, it also reinforces the model's credibility to the different stakeholders, and therefore the trust they can have in the results produced.
- Finally, during the production and presentation of results phase, in some cases the visualisation can provide more concrete illustrations of certain aspects such as bottlenecks, queues, etc. which are simpler to grasp visually than through indicators.

Current fast time simulation tools can nowadays be used for all the links in an airport chain, from airport access to terminal manoeuvring areas. Some tools also allow the connection of different modules in order to carry out complete simulations covering both aircraft and terminal levels. Most of the fast time simulation tools generally offer a few common basic functions which allow for a quick and efficient implementation:

- Importing CAD files to facilitate the infrastructure design step. These files generally require specific formatting (as each object must be added to a specific layer depending on its category to be recognised as such);
- Functions for setting operational rules adapted to the operation of an airport;
- Tools for the production and analysis of results. These can be integrated in the main tool for post simulation analyses and may allow for the visualisation of certain indicators during the simulation.

4.6.2.2. Limitations

While fast time simulation provides a number of advantages, it is also important to note that its implementation may present drawbacks that should be taken into account when defining the methodology of an analysis, and more specifically when selecting the tools and techniques that will be used to respond to the question that has been raised.

The first drawback is that the implementation of a model in a fast time simulation tool requires a significantly longer amount of time than in an analytical tool. Indeed, as the level of detail of fast time simulations is generally higher, the quantity of data required is also higher, which involves a much longer data gathering process. The modelling phase itself requires also a significant amount of time, whereas the use of an analytical tool is almost instant once all of the data has been gathered.

The second drawback is that the acquisition and maintenance of the modelling skills requires a more significant investment. While the initial training for the tool handling itself generally only takes a few days, it is necessary to dedicate a lot more time to master all its aspects and to be efficient when designing the models and producing results. Once these skills have been acquired, they must be maintained by carrying out studies at regular intervals, otherwise there is a risk of losing the efficiency that has been acquired. Given the cost of acquiring this type of tool, it is important to assess how much the tool is needed, not only at the time of the purchase, but also afterward throughout the time since it is necessary to perform regular analyses with such a tool in order to get a good return of investment from it.

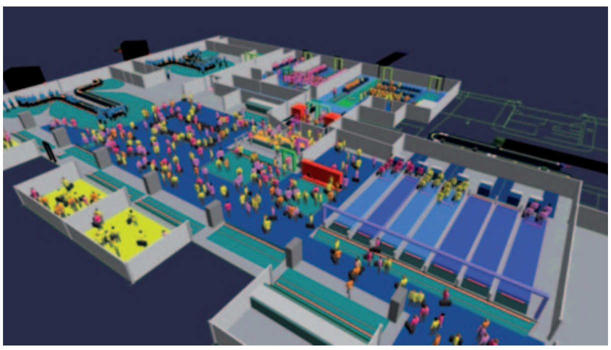


Figure 7: Modelling of a terminal and its different functions using simulation software

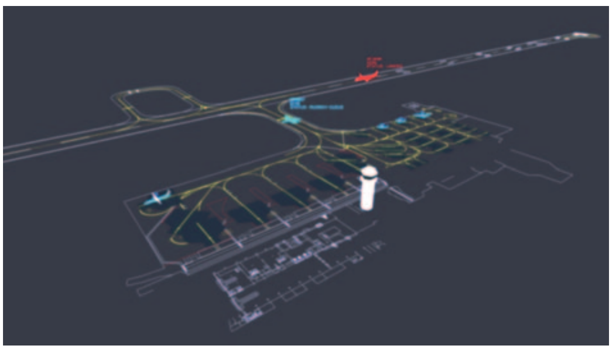


Figure 8: Modelling of the aircraft side of an airport and its different functions using simulation software

4.6.3. Real time Simulation

Figure 9: ENAC air traffic control real time simulator

Real time simulation is similar to fast time, but differs conceptually in one main aspect, which is that the time passes at the same pace as in reality. The reproduction of the real system can thus be more accurate and much less simplified than in a fast time simulator. A real time simulator can even integrate elements that are actually present in the real system in its architecture.

In the field of air traffic flow management, air traffic control simulators are the most frequently encountered real time simulators. Some of these simulators implement real human air traffic controllers as well as the very same working stations (same radar screen interfaces, same flight plan management system interfaces and software, same communication devices such as microphones, headsets and protocols, etc.) that are likely to be used in actual air traffic control centres. In such simulators, the simplification of the representation is limited to the modelling of aircraft, their behaviour and their exchanges with air traffic control (simulated radar returns, radio exchanges with "fake" pilots playing the role of real aircrews, etc.) and, where required, a 3D visualisation of the infrastructure and vehicles outside of the simulated control tower.

The benefit of this type of simulation is to provide a high level of credibility. Given the very close similarity between the real system and its representation, the bias introduced by these tools is in essence generally negligible with regard to the simulation objectives. A real time simulation therefore generally guarantees the reliability of the conclusions it allows to draw regarding the advantages or disadvantages of each simulated analysis scenario. Besides real trials on site, there is no more realistic way to assess the effects of a considered scenario.

However, the implementation of real time simulation is a significant task due to the human and technical resources to be mobilized and the time required to set up and then operate the simulator.

Their use within the scope of projects aiming to improve capacity therefore occurs usually at the final validation stage or to assist change management when the operating methods and details of the projects have already been refined. For the exploratory phases aiming to roughly shape the acceptable scenarios, real time simulations will be less adapted than analytical methods or fast time simulations.

4.7. Results

Once the simulations have been carried out, the final step is to produce the results based on the selected indicators. As indicated previously in the general methodology, this is a crucial step as the results will reflect all of the work carried out. Therefore, it is important not to leave anything out, in particular in the interpretation of the produced results.

The analysis of the results must in particular include a part explaining any seemingly anomalous behaviours, for example abnormally long waiting times or sharp increases in indicators. These behaviours may reflect either an error in the modelling or, if they are justified, the existence of a specific element in the operation of the system that warrants awareness. In this case, the explanation of the causes of this behaviour may prove useful to the operational stakeholders while reinforcing the credibility of the modelling.

The analysis of the variation of indicators between the reference situation and the modelled analysis scenarios must take into account the bias introduced by the modelling itself and which should have been measured during the calibration and validation phase.

The results may take different forms depending on the aim and the intended target audience. For example, they may be:

- graphics representing an indicator and its evolution;
- tables specifically formatted to highlight certain aspects;
- videos or screenshots (for simulation tools that have a display function) highlighting a certain situation.

Clearly, it is also possible to imagine other ways to present the results depending on their type. Different examples of results are shown in the figures below.

In Figure 10, a graphic presents the evolution of an indicator (the waiting time at a holding point for take-offs) between the reference scenario and two prospective scenarios corresponding to year 2019 and 2024 for which hypotheses concerning traffic and infrastructures have been established. The increase of traffic in the future scenarios therefore leads to an overall increase in the congestion at the holding point.

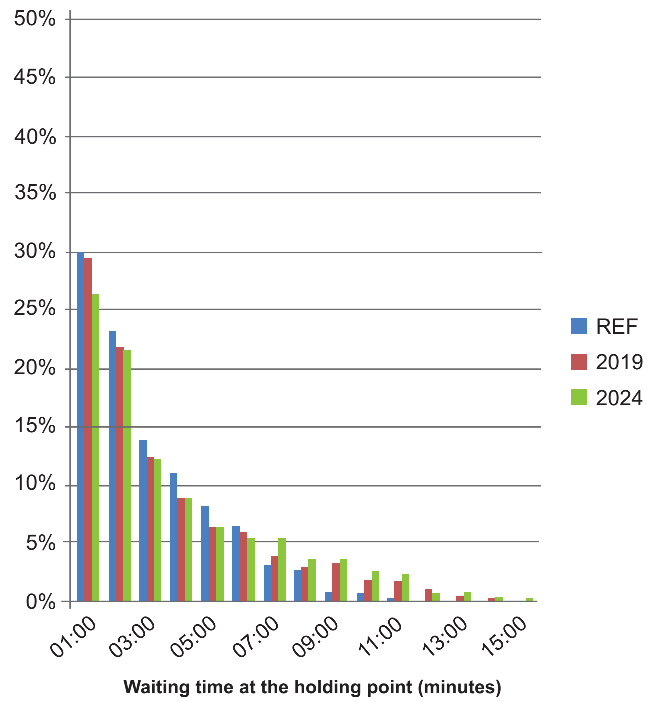


Figure 10: Example of indicators presenting the development of waiting times before runway access for three scenarios

In Figure 11, the table uses a colour code to represent the level of service provided to aircraft in terms of parking availability. If an aircraft is parked in a preferred position (i.e. corresponding to its wishes), the service provided is considered to be good, if not it is considered to be bad. The colour indicates the proportion of satisfied aircraft. This table presents the combinations of infrastructure and traffic scenarios in the rows, and the reference days selected for the analysis in the columns.

	24/07	26/05	29/05
REF			
2019 - S1			
2019 - S2			
2024 - S2			
2024 - S3			

Figure 11: Example of results presenting the level of service on the apron (aircraft parking) for several scenarios providing quick understanding

In Figure 12 there is an example of a screenshot from a fast time simulation. This screenshot conveys a visual idea of the delays at the holding point and the length of the queue. In certain cases, and in particular during discussions with platform operators, a visual of the simulated infrastructure may be clearer than the corresponding numeric plots.

Figure 12: Example of visual result produced with a fast time simulation

5. Methods for improving capacity

There are many ways to improve the capacity of an airport infrastructure. They can take varying amounts of time to implement, with more or less significant impacts on operations and may result in various degrees of improvement to the performance of the airport. For ease of understanding, these improvements are grouped into three main categories. These are:

- procedural improvements;
- system improvements;
- infrastructure improvements.

These categories are not strictly exclusive. An improvement primarily relating to one category may also involve minor improvements relating to the other categories.

In the rest of this chapter, we will look at each of these categories in detail by explaining them and providing some examples for each. The selected list is of course not exhaustive.

5.1. Procedural improvements

This type of improvements relates to a change of working methods in a broad sense for the operational personnel, without requiring them to use additional technical means.

5.1.1. RECAT-EU

RECAT-EU, which has recently been introduced at several major European airports, is a project to re-categorise the wake turbulence of aircraft. It aims to replace the four categories used currently (Light, Medium, Heavy and Super Heavy) with six new categories (Light, Lower Medium, Upper Medium, Lower Heavy, Upper Heavy and Super Heavy) and to associate new minimum separations to be respected between each of these different categories.

#1 \ #2	*Light* *MTOW < 7 t*	*Medium* *7 < MTOW < 136 t*	*Heavy* *136 t < MTOW*	*Super Heavy* *A380*
Light	*	*	*	*
Medium	*4 NM*	*	*	*
Heavy	*6 NM*	*5 NM*	*4 NM*	*
Super Heavy	*8 NM*	*7 NM*	*6 NM*	*

Figure 13: ICAO radar separation table

HEAVY RECAT-EU scheme		*« SUPER HEAVY »*	*« UPPER HEAVY »*	*« LOWER HEAVY »*	*« UPPER MEDIUM »*	*« LOWER MEDIUM »*	*« LIGHT »*
Leader/Follower		*« A »*	*« B »*	*« C »*	*« D »*	*« E »*	*« F »*
« SUPER HEAVY »	*« A »*	*3 NM*	*4 NM*	*5 NM*	*5 NM*	*6 NM*	*8 NM*
« UPPER HEAVY »	*« B »*		*3 NM*	*4 NM*	*4 NM*	*5 NM*	*7 NM*
« LOWER HEAVY »	*« C »*		*(*)*	*3 NM*	*3 NM*	*4 NM*	*6 NM*
« UPPER MEDIUM »	*« D »*						*5 NM*
« LOWER MEDIUM »	*« E »*						*4 NM*
« LIGHT »	*« F »*						*3 NM*

Figure 14: RECAT-EU radar separation table

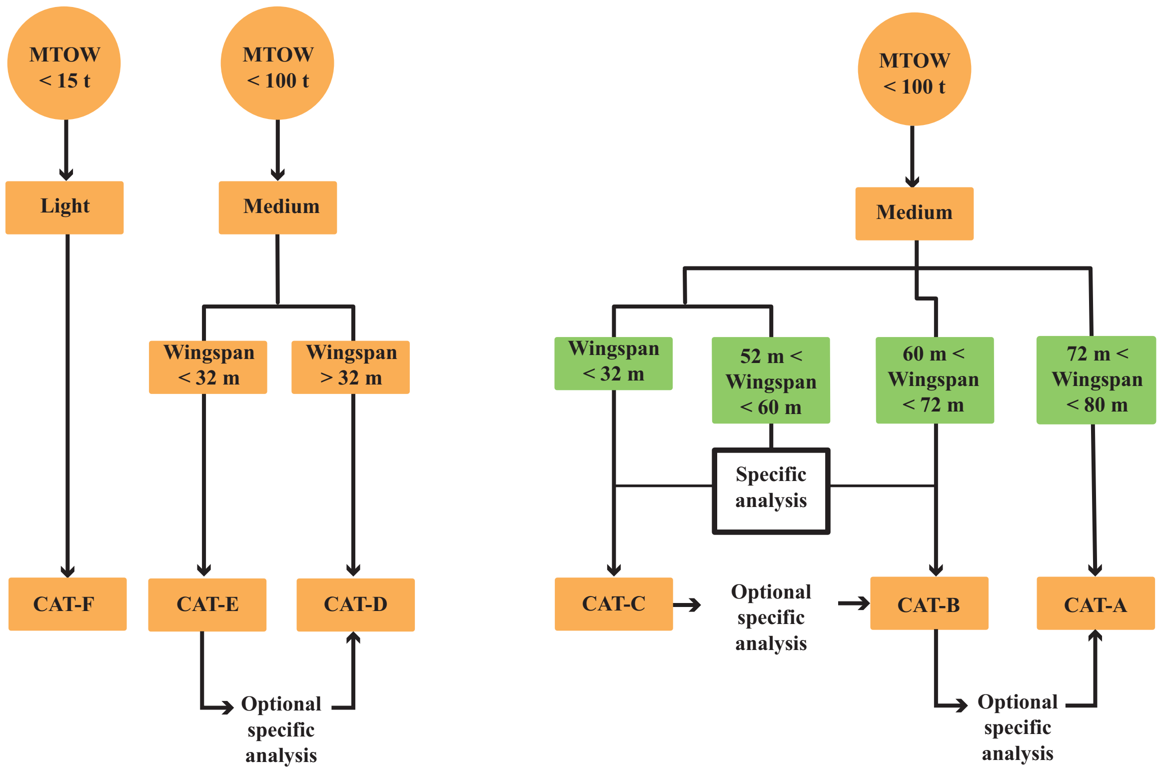


Figure 15: Diagram showing the conversion from ICAO categories to RECAT-EU categories

These new categories make it possible to adapt more precisely the separations to be applied between particular pairs of aircraft compared to their equivalent with the old categorisation, while aiming to maintain an equivalent level of safety. At major airports accommodating mainly public passenger transport, the RECAT-EU project thus makes it possible to increase the maximal capacity of the system, i.e. it is effectively creating capacity although only on the condition that no other element of the system becomes the limiting factor instead (such as runway occupancy time).

The RECAT-EU project also provides the advantage of allowing rapid deployment at airports, as it does not require modifications of existing infrastructures to be implemented.

5.1.2. Point Merge

Point Merge is a particular type of procedure used in terminal manoeuvring areas to allow for more efficient sequencing of aircraft on arrival at an airport.

This procedure consists of creating circular arc trajectories around a central point (the point where the trajectories merge - the merge point) that can be taken by aircraft when the traffic needs to be regulated. As the time it takes for an aircraft to reach the central merge point from any position on the circular arc is always the same (considering the speed of aircraft is constant), the flight time on the arc corresponds directly to the delay to be imposed to obtain the sequencing desired by the controllers (see Figure 16, diagram of the Point Merge situated north-west of the terminal manoeuvring area of Paris Charles de Gaulle airport).

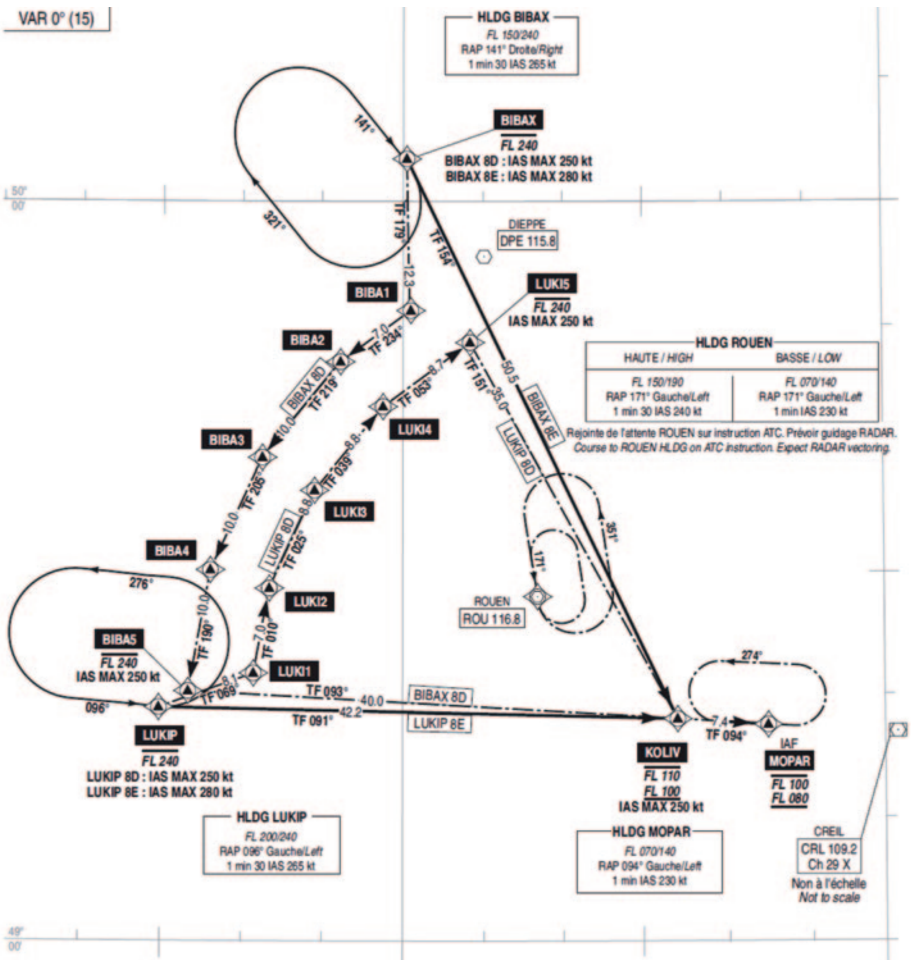


Figure 16: Extract from the aeronautical publication showing the merge point located in the north-west sector of the terminal manoeuvring area of Paris CDG airport.

The use of this type of procedure makes it possible to greatly improve the reliability of the expected arrival time of an aircraft compared to using a traditional racetrack holding pattern. This also makes it possible to reduce the controllers' work load as it is a more efficient method with fewer radio exchanges required to regulate the traffic.

While the implementation of such a procedure is not able to increase the maximal capacity of the system (the separations between aircraft are not reduced), by making the aircraft flow in terminal sectors more reliable (in terms of approach times and aircraft order) and by simplifying some of the the air traffic controllers' tasks, it allows for more efficient use of the available capacity and can thus contribute to increasing the operational capacity and most importantly the sustainable capacity of the system.

5.1.3. HIRO

The High Intensity Runway Operations (HIRO) project relates to a set of operational procedures for air traffic controllers and pilots that aims to reduce aircraft runway occupancy time at take-off and landing thus improving operational efficiency. These procedures, which do not require any change to infrastructures on the ground, consist among other things of:

- planning landing by identifying the appropriate runway exit to allow for efficient braking, minimising taxiing on the runway;
- reacting quickly to air traffic control instructions (line-up, take-off, runway crossing).

While these procedures on their own are not intended to allow for an increase in the programming capacity of a platform, the seconds that can be gained with each movement contribute to smoothing the departure and arrival traffic flows, and thus reduce delays and increase the operational and sustainable capacities of the infrastructure. These measures may prove to be indispensable when considering the implementation of measures that aim to reduce arrival separations as it is not possible to benefit fully from these new separations if there is an increase in the rate of go-arounds linked to runway occupancy times that last too long.

5.1.4. Facilitation of security screening

Facilitating the passenger preparation through better understanding of instructions and better assistance to those who require it is one way of smoothing the passenger flow at this mandatory checkpoint which often is a bottleneck in terminals. Better preparation provides advantages on several levels:

- Reduce the loss of time at the entry to the screening; it is possible to take advantage of the waiting time at the entrance to the security screening point to better inform passengers on how the screening will work, which will allow them to remove the necessary personal items as quickly as possible once they reach the loading belt.

Figure 17: The security screening point at Toulouse Blagnac airport allows several passengers to prepare at the same time

- Limiting the number of false alarms: a successful preparation of the passengers results in their not wearing any items that may cause false alarms when they walk through the screening equipment, and the correct extraction from their luggage of all items that should be removed from bags for scanning. This makes it possible to limit the number of alarms that require a second pass through the detection equipment or an additional search, both of which take up time and resources.

The passenger plays a full role in security. This new way of implementing security screening is an integral part in the strategic areas of focus developed within the scope of the Vision Sûreté program launched by the DGAC and which aims to improve and redevelop the procedures currently in place using a global approach that ensures the coherence and efficiency of the system.

5.2. System improvements

These improvements correspond to the implementation of new tools to be used by operators or updating existing tools. These can influence both the hardware and software components.

The impact on capacity is generally low, but may be considered critical at saturated airports where the slightest movement gained can represent a significant economic benefit and where it may be complicated to change the infrastructure.

Some examples are provided in the rest of this section for both runway and terminal sides.

5.2.1. Time-Based Separation et Pair-Wise Separation

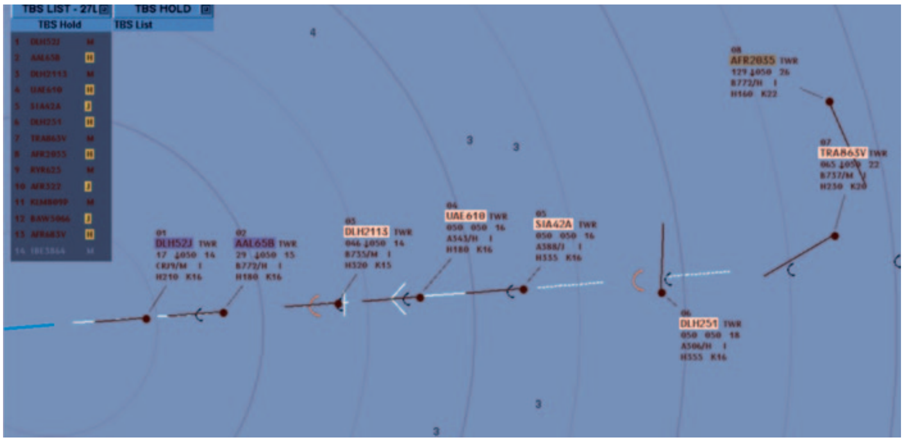


Figure 18: Extract from a TBS system radar screen showing the target chevron

Developed in recent years within the scope of the Single European Sky ATM Research Programme (SESAR), these new concepts make it possible to optimise the separations between aircraft on arrival, with the aim of reducing them in order to increase arrival capacity.

The concept of Time-Based Separation (TBS) involves using time separations instead of distance separations which are currently standard when controlling traffic using radar. The benefit of this concept is that it makes it possible to maintain a level of performance regardless of the intensity of headwind, as the aircraft throughput becomes independent from their ground speed.

In order to put this concept in place, it is necessary to add a Separation Delivery Tool system, which displays on the approach controllers' radar screens the distance that must be applied between two successive movements based on the adequate time separation. In other words, this new system transforms the time separation into a spatial separation so that it can be applied by the controllers. An illustration of such a system is shown in Figure 18. In this figure, the black chevron represents the desired separation that the approach controller must aim for given the risks of compression when aircraft slow down during final approach, and the red chevron represents the separation minima.

The concept of pair wise separation (PWS) is an extension of the RECAT-EU aircraft re-categorisation project which was recently implemented on major European platforms. While RECAT-EU has made it possible to change from four categories (Light, Medium, Heavy and Super Heavy) to six categories (A to F), PWS makes it possible to adapt the separation to each pair of aircraft. Therefore, there are theoretically as many categories as types of aircraft. Given the large size of the separation matrix as a result of the implementation of this concept, it is necessary to implement a similar system to that deployed using TBS. It should be noted that the following step of dynamic pair wise separation (D-PWS) is also being developed within the SESAR project. This involves expanding the PWS separation matrix using instant meteorological readings, measurements of the wake turbulence generated by the leading aircraft and data from the aircraft.

5.2.2. Radar minima

In mainland France, the main approach sectors are fitted with a radar that allows air traffic controllers to carry out assistance, monitoring and guidance of aircraft.

A standard is associated with each piece of radar equipment that corresponds to the minimum horizontal spacing distance between two aircraft at the same flight level. In French approach sectors, this distance is generally between 3 and 8 NM depending on the amount of local traffic. This standard is even reduced to 2.5 NM at major airports once the aircraft are aligned on the ILS axis. For information, a further reduction to 2 NM is being studied within the SESAR project.

The reduction of the radar minima by improving the systems (both the systems for acquiring and processing the signal) is a way of improving the capacity of a sector as well as facilitating traffic management for air traffic control. By reducing the radar minima, it becomes possible to bring aircraft closer to one another, which makes it possible to decrease the time intervals between departures and between arrivals considering the conditions on the ground are met to allow for the separations to be reduced.

5.2.3. Arrival Manager and Departure Manager

The aircraft sequencing management tools for arrival (AMAN, Arrival MANager) and departure (DMAN, Departure MANager) are now increasingly being systematically deployed at major airports across the world. They are systems that assist air navigation service providers in creating optimised sequences by taking into account a certain number of constraints and preferences in the management of all flows.

The concept is very similar for both systems. The tool gathers a list of all planned flights within a defined time frame including important information (e.g. the type of aircraft, the origin or destination, the planned movement time) and attributes to each of these flights expected times at specific points, as well as indicators making it possible to keep to these calculated target times.

In the case of DMAN, this will attribute in particular an intended take-off time as well as an intended off-block time taking into account the estimated taxiing time to reach the runway and the estimated waiting time to enter the runway to allow the aircraft to take off at the estimated time. By making this calculation for all planned flights for a defined time frame, it is possible to obtain an aircraft sequence for each of the airport's take-off runways.

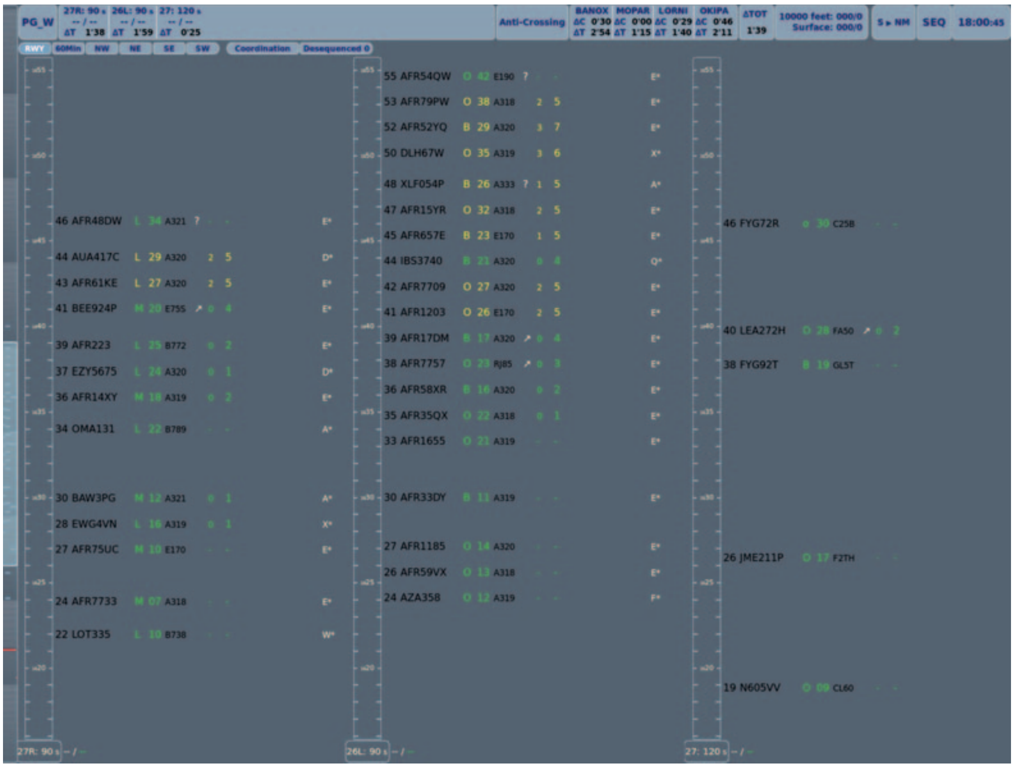


Figure 19: AMAN interface in the approach area to Paris Charles de Gaulle.
The two sequences on the left correspond to two arrival runways at Paris CDG airport,
the sequence on the right corresponds to the arrival runway at Paris Le Bourget airport.

The AMAN will calculate an intended landing time for each aircraft and provide controllers with indications on what to do in order to achieve this intended time. These indications may, for example, correspond to times that need to be gained or lost by an aircraft by altering its speed or its route.

These tools make it possible to use the available capacity in the most optimum way. While they are not intended to increase the maximal capacity of an infrastructure, they can allow to increase its operational capacity by means of an optimised management of aircraft flows. They are particularly useful during peak periods or when capacity is reduced due to external conditions (weather, maintenance works, etc.).

5.2.4. Passenger screening

Passenger screening (security screening and border control) is an element that frequently generates congestion in terminals. It involves passage points that are obligatory for all passengers on their journey through the terminal.

With the continuous increase in the number of passengers in transit at airports, the issue of maintaining an extremely high level of security while providing a throughput that can uphold the level of service provided to passengers is becoming a real challenge.

To be able to fulfil this essential task, new equipment and their associated new procedures have been implemented in airports in order to provide screening that is increasingly effective while also being quicker, so that the throughput at these screening points can be increased and thus improve passenger experience.

In terms of equipment, this could be new equipment capable of analysing more efficiently the passengers' cabin baggage, for example, by reducing the number of items that have to be removed from the baggage (laptops, liquids, etc.). This results in time saving in terms of preparation, the number of images to be analysed by the security staff and the number of alarms generated by poor preparation by passengers. In terms of border control, in recent years, automated border control systems have been deployed in different countries (PARAFE in France, ePassport Gates in the UK), making it possible to help holders of biometric passports move more smoothly through this type of screening point.

Figure 20: Automated border control gates at Paris CDG airport

5.3. Infrastructure improvements

Changes to infrastructures or the creation of new infrastructures have an impact on capacity that is generally simple to understand and easily visible. Infrastructure improvements generally involve adding new elements to different airport subsystems:

• **Runway**: an additional runway which can be used at the same time as the pre-existing runways leads to a capacity increase. It should be noted that maximal capacity is not always the parameter that motivates the creation of a new runway. In some cases, it may be issues with airport accessibility that motivate the creation of a new runway (prevailing winds in several directions, the addition of a backup runway in case the first runway becomes unavailable).

• **Taxiway**: the construction of new taxiways can improve ground traffic flows by decreasing the length of journeys, by providing alternate routes to operate ground crossings more simply or by making it possible to free certain areas more quickly. Among the most commonly observed taxiway network improvements, one can cite the examples of the construction of a taxiway running parallel along the full length of a runway (which avoids aircraft having to taxi on the runway), the construction of rapid exit taxiways (which make it possible to reduce the arrival runway occupancy time), or the doubling of taxiways to allow for crossings between movements in opposite directions.

• **Apron**: increasing the size of aprons makes it possible to increase the number of aircraft that can be parked at the same time. This type of improvement can be put in place in order to accompany the traffic growth, or to allow for the implementation of specific strategies for certain airlines, such as the creation of a hub (lots of aircraft arriving and then departing in a reduced amount of time to offer more efficient connections between flights) or the development of a base (aircraft parked overnight at the airport). This type of construction generally accompanies the development of infrastructures dedicated to processing passengers as a larger number of aircraft operating at the same time results in a larger number of passengers at the airport, which will require infrastructures that are dimensioned accordingly. Increasing the size of the apron may also be required in order to accommodate particular aircraft with dimensions that require specific facilities.

• **Terminal**: the construction or extension of a terminal makes it possible to increase the capacity to process passengers. During its design, several elements should be taken into account. For example:

  • The type of aircraft to be processed: for example the presence of wide body aircraft requires infrastructures that can hold a large number of passengers in a short period of time. This involves creating more subsystems (waiting areas, processing points, baggage carousels, etc.).

  • The type of airlines: low-cost airlines and high service level airlines will have very different expectations regarding the processing of passengers in the terminal. This will of course reflect on the level of service required in the terminal and therefore on the areas provided for passengers. Recently, we have been seeing increasing segregation between different types of airlines and the development of layouts with one side of the terminal providing a high level of service and the other side dedicated to low-cost airlines, making it possible to reduce the airport's operating costs.

  • The airlines' strategies: the presence of a hub at the airport, for example, will lead to constraints on the passenger infrastructures to ensure that connections between the different aircraft can be achieved easily in terms of connection journey time, or in terms of hold baggage handling.

  • The origin or destination of flights: the presence of international flights leads to the requirement for the terminal to have infrastructures making it possible to segregate flows from each other and requires the presence of State services for border control.

5.4. Example: Paris Charles-de-Gaulle airport

Paris Charles-de-Gaulle airport, the largest airport in France in terms of traffic, provides an interesting example to illustrate the issues of long-term planning and development of an infrastructure over the years.

When it was built initially, a large amount of land was secured for the development of the airport. The traffic increase opportunities and the urban development of the Parisian region made it necessary to save the space that would eventually be required to accommodate the estimated traffic in the ultimate time frame, even though it wasn't planned to construct all of the infrastructures immediately, but to set them up gradually alongside the growth of the traffic demand.

When it was opened in 1974, the airport only had one runway (the current runway 09R/27L), one terminal for passenger processing (the current terminal 1) as well as an area for maintenance and a cargo area. The initial infrastructure that was designed to hold approximately 10 million passengers was then progressively expanded as and when traffic increased. Since the 1980s, no less than 10 terminals and 3 runways have been added to the initial infrastructure:

- 1979 : Inauguration of the second runway (the current 08L/26R)
- 1982 : Addition of terminals 2A and 2B
- 1989 : Addition of terminal 2C
- 1991 : Creation of terminal 3
- 1993 : Addition of terminal 2D
- 1998 : Inauguration of the third runway (the current 08R/26L)
- 1999 : Addition of terminal 2F
- 2000 : Inauguration of the fourth runway (the current 09L/27R)
- 2003 : Addition of terminal 2E
- 2007 : Addition of boarding satellite S3
- 2008 : Opening of terminal 2G
- 2012 : Addition of boarding satellite S4 and the connecting building between terminals 2A and 2C

Other infrastructures are currently being constructed or planned to accompany the increase in traffic at the airport. For example:

- **The extension of terminal 1 (planned for 2020)**: this involves joining satellites 1 to 3 to create new buildings and to streamline operation at apron level.
- **Connecting terminals 2B and 2D**:in the same way as for terminals 2A and 2C, a new connecting building will make it possible to connect the two terminals. This project involves reconfiguration of space within the terminals.
- **Terminal 4 (in planning)**: the increase in traffic in the long term will lead to additional needs, which will require the construction of a new terminal. This would be realised to the north of terminal 2 and the east of terminal 1 in an area that does not yet have passenger infrastructures.

The total annual capacity of the passenger-side infrastructures should exceed 80 million passengers by 2025, then 120 million passengers with the construction of terminal 4. It is certainly interesting to compare these values to the initial 10 million passengers at the airport's opening. With almost 70 million passengers in 2017, Paris Charles-de-Gaulle airport still has room to pursue its growth.

At the same time as the infrastructures on the ground are being developed, the processes and systems are also improved to allow for additional traffic. Radar detection systems have been improved to reduce the spacing between aircraft, air traffic procedures have been adapted over time to adapt to both new infrastructures (notably the new runways) and to new concepts that have developed over time. Examples of these developments include:

- Deployment of the AVISO tool for aircraft surveillance from the ground (A-SMGCS);
- Introduction of the sequencing tools for arrival (AMAN) and departure (DMAN/GLD);
- Gradual reduction of the radar separation standard to reach 2.5 NM today;
- Implementation of new separations based on RECAT-EU and the HIRO project;
- ...

However capacity is clearly not the only motivation for these developments. Questions of operation safety and security also play a leading role in the development of an infrastructure.

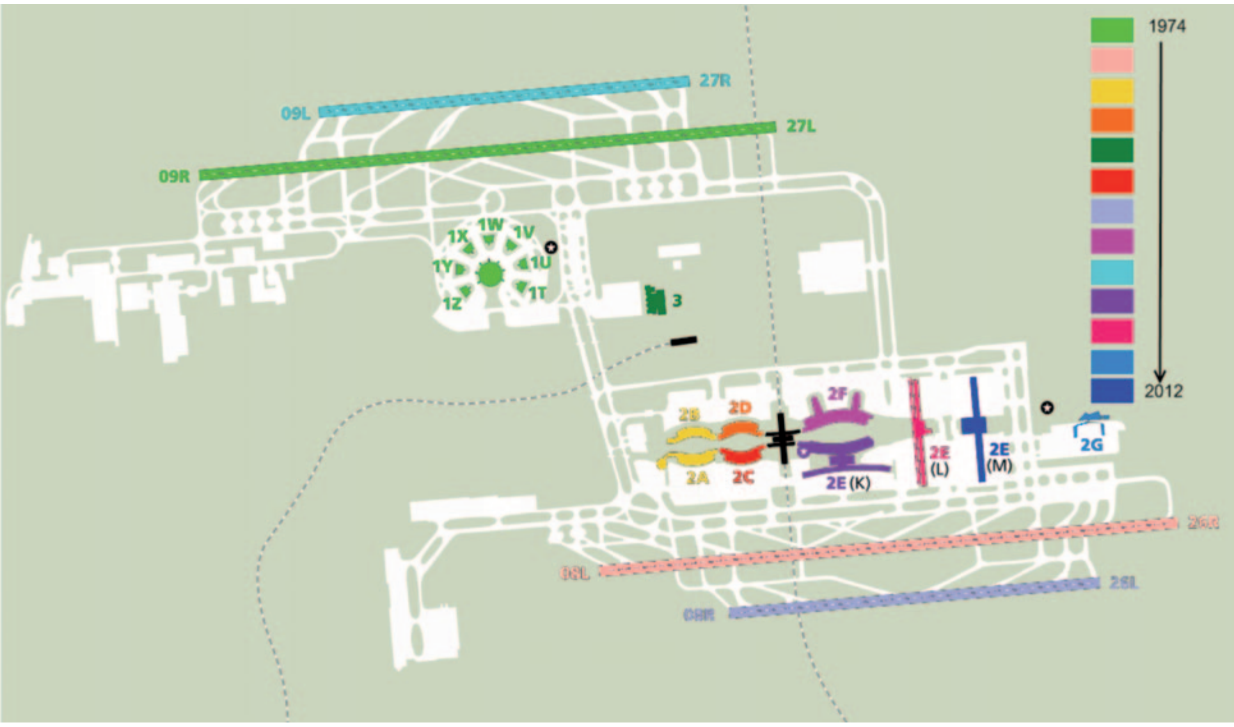


Figure 21: Schematic representation of the development of infrastructures on the ground at Paris CDG airport

Whatever the reasons guiding the development of an airport, it is important to highlight the importance of adopting a long-term vision of its development and the example of Paris Charles-de-Gaulle shows that planning in the 1970s for needs that would not become apparent for several decades has led to the benefit of having a substantial amount of land available for further development today.

The development of infrastructures themselves needs to be staggered over time to avoid having to manage an overdesigned system for a significant amount of time. One of the purposes of long-term planning is therefore to ensure coherence and continuity in the development of facilities, in particular to avoid as much as possible the need to deconstruct a previous layout to allow for a subsequent development.

This is one of the main difficulties in long-term planning as the development of technologies, regulations or the environment of an airport may make large parts of the initially conceived development plan invalid. Therefore, it is necessary to continuously adapt the long-term planning in response to developments of the context in which the airport finds itself, while still enforcing and preserving a coherent orientation in the progressive development of its infrastructure.

WRAP-UP

Capacity; a global problem with multiple challenges

While the capacity of an airport system may seem to be expressed in a simple manner, in reality the number of elements hidden behind this value is extremely high. Numerous factors have a more or less direct impact on the capacity and it is necessary to regularly consider a system in its entirety to be able to assess it accurately in the short, medium and long term.

Managing capacity though the creation and regular update of documents such as master planning documents is necessary to respond to the expected increase in demand, the planning of developments or the planning of operations. The development of the capacity must be considered as far upstream as possible in order to identify, evaluate and adapt as early as possible to implications (positive or negative) that the increase of traffic may cause in the environment in which the airport is located in terms of urbanisation, environment or employment. Detailed knowledge of the relationship between an increase in capacity and the impact of its implementation makes it possible to plan developments more accurately for the benefit of users while disrupting the service as little as possible.

Finally, assessing capacity may provide a valuable decision-making aid in order to optimise the operational capacity, in particular in adverse situations within the scope of collaborative decision mechanisms (A-CDM) deployed at the airport and for air traffic flow management (ATFM).

Knowing the capacity of all of one's infrastructures allows for a focused and efficient development from an economic point of view. Anticipating future needs is essential in order to ensure the viability of a system. By taking into consideration the estimated development of its traffic with its actual or estimated capacity, it is possible to react proactively and to implement the most appropriate solutions, which may not necessarily require the construction of new infrastructures.

This is an indispensable step in implementing a capacity management system to provide the greatest benefit to users and all stakeholders of an airport.

Glossary

TERMINAL
Installation allowing for the loading and unloading of aircraft and the processing of their commercial load (passengers/freight).

DEICING AREA
Specific areas of the infrastructure where aircraft are presented to be de-iced (removal of ice from the aircraft and application of a liquid temporarily protecting the aircraft from the formation of ice).

MOVEMENT AREA
Group made up of the manoeuvring area and the apron.

APRON
All aircraft parking areas and the taxiways serving these.

ON-BLOCK TIME
Time at which an aircraft arrives at its stand.

GROUND HANDLING
All services, apart from air traffic control, provided to aircraft on the ground during the transition phase between arrival and departure.

MAXIMAL CAPACITY
Quantity of traffic that can flow through an infrastructure in saturation conditions, in compliance with the applicable regulations but with no consideration regarding the resulting level of service.

OPERATIONAL CAPACITY
Quantity of traffic that can flow through an infrastructure in compliance with the applicable regulations and taking into account a defined level of service.

SUSTAINABLE CAPACITY
Quantity of traffic that can flow through an infrastructure in a sustainable way. This refers to the ability of operators to maintain a level of performance over a long period of time and to reproduce this level of performance accounting for variaility sources such as human factors.

CLEARANCES
Authorisations from air traffic control to aircraft.

AIR TRAFFIC CONTROL
The service provided to aircraft to ensure that they can progress safely.

COORDINATION
A binding means of traffic demand management at an airport.

REPORTING PROFILE
Profile representing the development of the cumulative percentage of passenger arrivals at the airport by time.

SLOT
Departure or arrival time of an aircraft at its stand, which is agreed as part of the coordination or facilitation of an airport.

OFF-BLOCK TIME
Time at which an aircraft leaves its stand.

CHECK-IN
Action to confirm a passenger's intention to travel to the airline and, if necessary, to drop off hold luggage.

TERMINAL MANOEUVRING AREA
The part of the airspace situated around the airport making it possible to transition between the airport and cruising.

AIRPORT OPERATOR
The entity responsible for the management of an airport.

FACILITATION
A non-binding means of traffic demand management at an airport.

AERONAUTICAL INFORMATION PUBLICATION
All information relating to the geometry of infrastructures, operating procedures and rules of an airport published by the national authorities.

SECURITY SCREENING
Screening passengers and their luggage to ensure operational security.

AIRCRAFT MOVEMENT
Departure or arrival.

CONVENTIONAL NAVAIDS
Means to aid navigation of aircraft from or to the radio beacons located on the ground.

AIR NAVIGATION SERVICE PROVIDER
The entity that provides the air traffic control service.

(AIR NAVIGATION) PROCEDURE
Series of predefined manoeuvres allowing an aircraft to progress between the entry or exit point of the terminal manoeuvring area and the airport.

OPERATING PROCEDURES
All rules that regulate the progress of operations in an airport system.

AIR TRAFFIC MANAGEMENT
Action to control air traffic while respecting the minimum required spacings.

AERONAUTICAL SEASON
Period of six months starting on the last Sunday in March for the summer season, and the last Sunday in October for the winter season.

OPERATING DIRECTION
Direction in which a runway is used (generally connected to the wind direction).

RUNWAY PROTECTION AREA
Area around the runway with the aim of protecting take-off and landing operations from the risk of collision or interference.

TRAFFIC MIX
The proportions of different categories of entities that make up the flow.

TAXIWAY
Infrastructure allowing for taxiing of aircraft on the ground at an airport.

Appendix 1: Bibliography/ Recommended literature

To expand on the concepts presented in this document, you can find more information in the following reference publications:

- ICAO Doc 9184 – Airport Master Planning Manual
- ICAO Doc 9157 – Aerodrome Design Manual
- ICAO Doc 9971 – Manual on Collaborative Air Traffic Flow Management
- ICAO Annex 14
- IATA – Airport Development Reference Manual
- ACRP Report 79 – Evaluating Airfield Capacity
- ACRP Report 25 – Airport Passenger Terminal Planning and Design (Volume I & II)
- ACRP Report 55 – Passenger Level of Service and Spatial Planning for Airport Terminals
- EUROCONTROL – Airport Capacity Assessment Methodology
- Planning and Design of Airports, Fifth Edition (R. Horonjeff & al.)

Numerous scientific articles from different universities and research facilities across the world that handle these questions, a detailed list of which is not provided here, can also be consulted.

Appendix 2: Examples of analytical calculations

Example 1 : Runway capacity

The probabilistic method is a simple method for assessing the capacity of a runway system. It provides macroscopic results, which make it possible to get a general idea of the performance of the infrastructure considered. To implement it, it is necessary to know:

- the traffic mix at an aggregated level;
- the final approach speeds of aircraft;
- the separations required between two successive movements;
- the runway occupancy times.

Let's take the following example: a single runway used exclusively for arriving aircraft, associated with traffic made up of 60% A320 medium-haul aircraft, 20% ATR 72 medium-haul aircraft (turboprop) and 20% A330 long-haul aircraft.

The first step consists of determining the probability of encountering each pair of aircraft. These probabilities are expressed as follows:

$$p_{ij} = p_i{}^{*}p_j$$

Where :

- p_{ij} corresponds to the probability of encountering the pair i,j;
- p_i and p_j correspond respectively to the probability of encountering the categories i and j.

For example, the probability of encountering two successive long-haul aircraft is 20 % x 20 % = 4 %. Therefore, the probability matrix is as follows:

	ATR 72	*A320*	*A330*
ATR 72	*4 %*	*12 %*	*4 %*
A320	*12 %*	*36 %*	*12 %*
A330	*4 %*	*12 %*	*4 %*

A simple verification method consists of ensuring that the sum of p_{ij} in the matrix above comes to 100 %.

In the same way, the matrix of separation between the different types of movements needs to be determined. This separation will depend on various different factors, such as the runway occupancy time, which primarily depends on the geometry of the infrastructure (quantity and type of exits) or on the radar separation minima in the terminal manoeuvring area. Let's consider the following matrix of separation on arrival (leader aircraft in the rows, the follower aircraft in the columns) and make the simplifying hypothesis that the runway occupancy time is not restrictive:

	ATR 72	*A320*	*A330*
ATR 72	*3 NM*	*3 NM*	*3 NM*
A320	*3 NM*	*3 NM*	*3 NM*
A330	*5 NM*	*5 NM*	*4 NM*

This distance separation on arrival may be translated into a time-based separation by using the following approach speeds (considered as constant over the 5 NM final approach):

- ATR 72 – 120 kts
- A320 – 135 kts
- A330 – 145 kts

Therefore, we obtain the following time-based separation matrix (corresponding to the time required to travel the separation at the approach speed of the follower aircraft):

	ATR 72	*A320*	*A330*
ATR 72	*90 s*	*80 s*	*75 s*
A320	*107 s*	*80 s*	*75 s*
A330	*175 s*	*143 s*	*100 s*

In this matrix, the figures in red take into account the speed differential between the aircraft. As the separation must be maintained for the entire final approach, when faster aircraft are followed by slower aircraft, the separation at the end of the final approach will be larger than the minimum prescribed separation since the leading aircraft will pull away from the following aircraft throughout the final approach.

The final step consists of calculating the average separation, which consists of intersecting the probability and separation matrices:

$$C_m = \sum_{ij} p_{ij} \, s_{ij}$$

In our example, we obtain an average time interval of 95 s, which corresponds to a capacity of **37 arrivals/h.**

It is possible to expand this method to determine the capacity of a runway used both for take-offs and landings. To do this, the following three cases should be considered:

- The case of successive departures: the separation matrix is generally directly defined in terms of wake turbulence constraints, runway occupancy times, and airspace constraints.
- The case of a departure followed by an arrival: the separation is restricted by the departure runway occupancy time, no matter the type of arrival. It is therefore possible to relatively simply establish the matrix of time-based separations required between the possible departure/arrival pairs.
- The case of an arrival followed by a departure: the separation is restricted by the arrival runway occupancy time, no matter the type of departure. It is therefore possible to relatively simply establish the matrix of time-based separations required between the possible arrival/departure pairs.

Based on these different matrices, it is possible to calculate the average separation by taking into account the probabilities of an aircraft being a certain type and the probabilities that it will be an arrival or a departure.

Note:

- **This method provides theoretical capacity results that should be refined by taking into account operational margins. To avoid falling below the radar separation minima or to limit the number of interrupted approaches, air traffic controllers never operate an infrastructure exactly at its limit.**
- **The method and example presented here are deliberately simplistic. For example, there are infra-structures where the radar separations at arrival are not the limiting factor, infrastructures with several line-up positions at departure resulting in additional constraints on the separations between take-offs, infrastructures with a displaced landing threshold imposing constraints on wake turbulence between arrivals and departures, or even airports where the constraints between departures and possible missed approaches, must be taken into account.**

Example 2: Check-in area capacity

The second example involves calculating the capacity of a check-in area in a terminal. We will take the following example:

- 7 check-in desks;
- a waiting area of 100 m².

We make the hypothesis that all the counters are operated in the same way without any particular distinction and that all passengers require the same amount of time for baggage check-in processing.

A certain amount of data is required to carry out this calculation:

- the processing time for a passenger at check-in : 90 secondes;
- the waiting area ratio (level of service) : 1.8 m²/pax (IATA Optimum);
- the maximum waiting area ratio (level of service) : 10 minutes (IATA Optimum).

To assess the hourly capacity of 7 check-in desks, we will use the following formula:

$$C_b = N_b \frac{3600}{T_b}$$

Where :

- N_b is the total number of check-in desks.
- T_b is the processing time for a passenger (in seconds).

With 7 check-in desks and a processing time of 90 s, we obtain an hourly processing capacity of 280 pax/h.

For the check-in area, as a first approximation, it is possible to use the following formula:

$$C_a = \frac{S}{R} \frac{60}{T_{wait}}$$

Where:

- S is the area of the waiting area (is m²).
- R is the ratio of area (level of service).
- T_{wait} is the maximum waiting time (level of service, in minutes). In our example, we obtain an hourly capacity of 333 pax/h.

The capacity of the entire check-in area finally corresponds to the smallest of the two values. In our example, the capacity of the entire check-in area is therefore determined by the processing capacity of the check-in desks themselves, which is 280 pax/h.

Example 3: Apron capacity

The final example involves the assessment of the capacity of an aircraft parking area. Here we will use Horonjeff's method, which requires the following data:

- the total number of stands;
- the proportion of aircraft of each category;
- the average rotation time for each category.

In this example, we consider a parking area with 20 stands, with traffic split into three categories (60% A320, 20% A330 and 20% ATR72).

For each category, we assume the following turnaround times:

- ATR7 : 30 minutes
- A320: 45 minutes
- A330: 2 h 30 min

The calculation of capacity is carried out using the following formula:

$$C_{APRON} \leq \frac{u \times N}{\sum_i p_i \, T_i} \qquad \text{(A3-3-1)}$$

Where:

- N corresponds to the total number of stands;
- u is the coefficient of use of the stands set at 0.85 here. It represents an operational margin making it possible to absorb a possible delay;
- p_i is the proportion of aircraft of category i;
- T_i if the average rotation time of aircraft of category i.

Therefore, in our example we obtain a parking area capacity of 16 aircraft/h, which is approximately 10 A320s, 3 A330s and 3 ATR72s. It should be noted that these 16 aircraft/h correspond to 32 movements/h, as a rotation is made up of an arrival movement and a departure movement.

This method is a first estimation, which in particular considers that all the stands can be used at the same time and occupied by all aircraft.

It is possible to refine this method by considering the stands separately according to the category of aircraft that they can handle. Here we consider that only a proportion of the stands can be used by the A330 long-haul aircraft, with the following distribution:

- 8 long-haul stands (which by extension can also hold smaller aircraft) with a coefficient of use of 0.85.
- 12 stands can only hold the medium-haul aircraft (ATR72 and A320) with a coefficient of use of 0.85.

In this case we obtain two subcategories of demand:

- The demand for the stands able to hold long-haul aircraft. In our example, this corresponds to 8 stands. These stands must respond at least to the demand of long-haul aircraft.
- The demand for the stands able to hold medium-haul aircraft. Here, 20 stands are available; 8 mixed stands (long-haul/medium-haul) and 12 medium-haul stands. These 20 stands must respond to the whole of the demand; the medium-haul aircraft (ATR72, A320), but also the long-haul aircraft, which can only use the 8 mixed stands.

The formula above (A3-3-1) must remain true for these two specific cases. The whole of the parking area must therefore satisfy the following two formula:

$$C_{APRON} \leq \frac{0.85 \text{ x } 8}{0.2 \text{ x } 2.5} = 13.6 \text{ aircraft}/h$$

$$C_{APRON} \leq \frac{0.85 \text{ x } 8 + 1 \text{ x } 12}{0.2 \text{ x } 2.5 + 0.6 \text{ x } 0.75 + 0.2 \text{ x } 0.5} = 17.9 \text{ aircraft}/h$$

Here, the capacity is limited by the first formula, i.e. by the parking of long-haul aircraft. In effect, it is not possible to process more than 13.6 aircraft/h with only 8 long-haul stands given the distribution of traffic and the rotation time defined in this example. Effectively, this means that in extreme cases where no stands can hold long-haul aircraft, the capacity of the parking area would be zero, as the distribution dictates 20 % long-haul aircraft.

In the case where all stands are mixed (long-haul/medium-haul), with this variation of the method we find the same results as those of the equation of the previous example.

Design: STAC/SINA Documentation and dissemination of knowledge (DDC)

Cover: © Vincent COLIN DGAC/DSNA

Inside pictures: © ENAC page 44
© Antoine LAMIELLE CC BY-SA 4.0
Wikimedia Commons page 54
© Richard METZGERT DGAC/STAC pages 17, 50
© Laurent MIGNAUX-Terra page 59
© Steve MORRIS page 25
© Véronique PAUL DGAC/STAC page 29

Illustration/Chart: © SNA-RP pages 51, 53
© Département ACE DGAC/STAC pages 43, 46
© Département ACE DGAC/STAC pages 43, 46
© SIA page 49

September 2020

service technique de l'Aviation civile
CS 30 012
31, avenue du Maréchal Leclerc
94 385 BONNEUIL-SUR-MARNE CEDEX
Tél. +33 1 49 56 80 00
Fax +33 1 49 56 82 19