

AIRPORT CAPACITY DYNAMICS:

A 'PROOF OF CONCEPT' APPROACH

by

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Abstract

The continuing growth in aviation has meant that the 35 largest airports in Europe reached saturation in 2005. The consequences have been increasing air traffic congestion, delays and associated costs. There is therefore a clear need to create more capacity. However, airports in particular and the air transport system in general are also subject to sudden fluctuations in demand and capacity. This research synthesizes the mechanisms of airport capacity fluctuations through the analytical formulation of concepts of capacity dynamics, capacity elasticities and capacity stability. It demonstrates the usability of these concepts through, firstly, a case study application to Brussels National Airport and, secondly, the development of a 'proof of concept' decision-support tool for strategic and tactical airport planning. Capacity dynamics and elasticities provide a performance indication as to how quickly capacity is able to change in response to fluctuations brought about by one or more capacity disrupters, whilst capacity stability provides airport planners with a measure of capacity robustness.

These three concepts - capacity dynamics, elasticities and stability - contribute to a better *a priori* understanding of the airport system to be modelled. They demonstrate a better quantification of the impact and sensitivity of all the factors that affect runway capacity. It is also shown how the three concepts can assist in a better quantification of the risk of potential capacity fluctuation within the scope of airport planning. Based on this analytical formulation and quantification, mitigation should be an integral part of any effective airport plan in order to predict better the response to any given potential capacity degradation. It has been found that, from a capacity perspective, an airport becomes less stable the higher its level of performance. This capacity/stability paradox enables the ultimate goal of investment in capacity enhancement to be challenged, and it is legitimately questioned whether a similar investment would not be more worthwhile at secondary airports rather than at major airports.

Keywords: airport planning, airport modelling, capacity analysis, capacity dynamics, capacity elasticity, capacity stability.

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Research is all about rushing into a tunnel with a feeling of never-ending, but with the intense wish of seeing light again, and with the particular hope that this light is not coming from a facing train, in which case research fails! But when daylight appears again, sun is definitely shining more than ever upstream!

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*In addition to quantifying
what intuition can qualify,
modelling is the art of predicting
what intuition cannot.*

To my wonderful family,
without whose dedicated
support over many years,
this interest would have
never been fulfilled.

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Chapter 1 - Introduction

1.1 Research Statement: The Facts of the Matter

For many decades following the invention of civil aviation, flying was the preserve of the wealthy. It was also used by States to demonstrate to the rest of the world their economic power and advanced 'quality of life'. Carrying the flag became a symbol of political power. Since the 1960's, however, air transportation has become without doubt a vital element of people's lives around the world. With the entry of low cost carriers, air transport has also become more democratic. Whilst enabling people to meet all over the world, air transport stimulates economies, global trade and tourism (SESAR, 2006a).

Traffic demand has become increasingly diversified in terms of both services provided and accommodated types of aviation vehicles. New Large Aircraft (NLA), Very Light Jets (VLJ's) and Unmanned Aerial Vehicles (UAV's) are just some examples of the diversification of the coming demand in air transport. Air transport also requires greater interaction between the various actors who generate traffic demand. Flexible Use of Airspace (FUA) sets up the co-operative framework between civil and military aviation in Europe in order to maximize the use of airspace, whilst the Collaborative Decision-Making (CDM) concept takes this form step-by-step under various guises in the US and Europe.

In Europe, ICAO records 2,234 airports in 36 countries who are members of the European Organisation for the Safety of Air Navigation (EUROCONTROL), of which 1,986 are in 25 countries of the EU (SESAR, 2006a). Of the total, 766 are recognised by IATA as commercial airports. Those 766 airports generate a total of about 135,000 direct jobs. 1.23 billion passengers were accommodated in 2004, together with 15.5 million tons of cargo, for a total of 17.7 million movements. In 2004 again, the aeronautical revenues of European airports, which is about 50% of their revenue, reached €11.22 billion.

Between 2006 and 2020, global Gross Domestic Product (GDP) is forecast to grow at an average annual rate of 3.5%. The increase in worldwide GDP will lead to an increase of air traffic demand. About 23,000 IFR (Instrument Flight Rules) flights were accommodated during peak days over the ECAC (European Civil Aviation Conference) area in 1993; 32,000

flights were recorded during the peak day in 2006 over the same area. The overall demand for air transport is expected to increase by 4.2% per annum. As a result of growing GDP, it is anticipated by 2020 that the annual European traffic demand will be double that of 2005. With 9.1 million IFR flights in 2005, this translates into approximately 18 million IFR flights by 2020 (SESAR, 2006b). During the busiest months of the year, the European ATM system should be able to accommodate 50,000 flights a day around 2022. The total added value of air transport to European GDP could be up to €470 Bn by 2020. It is therefore necessary to ensure the sustainable growth of air transport.

Growth at high-density airports is limited. The 35 largest European airports have reached saturation in 2005. EUROCONTROL (1998) claimed that there were 19.5% of intra-European flights delayed for more than 15 minutes in 1997, i.e. 7.5 million flights. The average delay per flight was 1.9 minutes in 2005 (SESAR, 2006a), and was shared on average 50% by airports and 50% en-route. With regional airports working at full capacity, existing airport capacity in Europe will be reached between 2013 and 2015 (SESAR 2006a). If traffic demand doubles between 2005 and 2020, some European airports will struggle to accommodate such growth. According to EUROCONTROL (2004), about 60 airports will be congested by 2020, and the top 20 airports will be saturated for between 8 and 10 hours a day.

Many factors cause the increase in air traffic congestion, delays and associated costs. According to Caves *et al.* (1999), the most important factors are steadily growing demand combined with the lack of sufficient system capacity, operating practices of many airlines materialising through hub-and-spoke networks, and different environmental constraints affecting both expansion and efficient utilization of the available system capacity. The industrial actions in Europe, together with bad weather conditions, are shown to be the most important factors of airline and airport schedule disruptions, and consequently congestion, delays, diversions and even cancellations of flights (Janic, 2003). The lack of accuracy of weather forecasts undoubtedly constitutes a real cause of delay. According to EUROCONTROL (2005), around 40% of airport air traffic flow management (ATFM) delays and 10% of en-route delays are initially due to weather, unless is it due to inefficient planning of adverse weather conditions? Current operational practices at Schiphol Airport show that forecasts of extreme weather conditions are only accurate 30% of the time. This results in 10 to 15 situations a year where flow restrictions are not adapted to actual weather conditions; consequently capacity cannot be used to its full potential.

In April 2004, the European Commission (EC) initiated the Single European Sky (SES) performance-based framework, with the intention of changing the future structure of air traffic control across Europe. The ultimate objective is to replace step-by-step the present air traffic management (ATM) working arrangements, which are largely based on national boundaries, by a more efficient ATM system based on actual flight patterns. The aim in the shorter term is twofold: first to synchronize the plans and actions of the different ATM stakeholders throughout Europe and, second, to federate resources for the development and implementation of the required improvements of ground and airborne ATM systems. The Single European Sky strategy raises, strengthens and consolidates awareness in the air transport industry that the growth of air transport cannot be sustainable without a firm ATM performance partnership: all the stakeholders need to have a shared understanding of the need to optimise collectively the ATM system performances, and agree on targets and trade-offs. In support of SES, the EC also initiated the SES Air Traffic Management Research and modernization programme (SESAR). SESAR is certainly the most ambitious programme ever initiated in Europe in response to the ATM challenge. As expressed by the EC Vice-President Jacque Barrot, the objectives of the SESAR programme are fourfold: first, to enable a three-fold increase in capacity in order to reduce delay on the ground and in the air; second, to improve safety by a factor of 10; third, to enable a 10% reduction of the environmental impacts; and fourth, to provide ATM services at a cost which are at least 50% less in comparison with today performance (SESAR, 2006b). According to EUROCONTROL (2005), the total ATM costs for European gate-to-gate traffic was €800 per flight; the cost-effectiveness target set up by SESAR aims at halving this ATM cost. The target for capacity enhancement in particular is that the European ATM System (EATMS) can accommodate a 73% increase in traffic by 2020, based on 2005 baseline, whilst meeting the targets for safety and quality of service.

Beyond the EC Single European Sky initiative, there are two major stumbling blocks to accommodating this traffic demand increase. The first comes from the fact that our planet undoubtedly suffers from global pollution coming from various sources, air traffic in particular. The second constraint, in Europe, is the lack of infrastructure at airports that may limit growth to 3.4% per annum (compared with 4.2% for unconstrained demand). By 2020, growth in air traffic will be constrained to be 1.7 times higher than 2005 (compared to 2 times if unconstrained), resulting in the inability to accommodate 2 million IFR flights due to lack of airport infrastructure. Should it be the case, there could be a potential annual loss to Europe

of about €50 billion of added value in 2020. In 2025, this loss could be as great as €90 billion and 1.5 million jobs.

There is therefore a clear need to create more capacity to ensure that the European economy remains competitive and to ensure the most efficient ATM operations. Airspace users place demand for capacity upon airports in terms of the infrastructure (e.g. runways and terminal facilities). Several capacity enhancement initiatives took place in Europe during the last decade. For instance, one of the most recent mega-projects is the construction of the new Berlin Brandenburg International airport that started in 2006, and which is planned to be operational by 2011. This new airport, which is expected to take over air traffic from the three existing airports in Berlin, is planned to accommodate between 22 and 25 millions passengers a year, with the possibility to reach 40 million passengers a year. The investment is estimated to be €2.6 billions, and could create 40,000 new jobs, according to the airport authorities (Berlin, 2006).

Building new runways and terminals is an obvious solution to capacity provision, but it is also by far the most expensive one. In addition, very few greenfield airports are expected to be developed in Europe over the next 20 years because of ecological and land management considerations. Other solutions therefore consist of developing new technologies and procedures that can optimise the use of the available airport capacity. Another solution, probably complementary, is to release and take maximum benefit from existing latent capacity by enhancing capacity management. In Europe, the utilisation of airports varies significantly; some have capacity shortages whereas many do not. This latter issue of latent capacity directly addresses capacity management efficiency.

The ATM network, whose airports can definitely not be walled up from, are subject to sudden changes in demand and capacity. There are, and there will always be some unpredictable events that will remain detrimental to air traffic demand in general, and to both airports and airspace (for overflights) in particular. For instance, it is largely recognised on the international scene that the event of 11th September 2001 and, consequently, the Iraq crisis have had tremendous impact on traffic all over the world. It could be read in the press that, for instance, "*passenger traffic at Vienna International Airport fell 0.5% year-on-year, as the positive trends of early 2003 were slowed by the war in Iraq*" (Reuters, 2003b), or "*offset risks brought on by Iraqi war impeded a fuel surcharge of 0.20€ per kilogram of freight in German airline Lufthansa*" (Reuters, 2003a). Sometimes, unpredictable events can also be favourable to air transport. For instance, despite the facts that the international tension

related to the Iraq crisis and the severe acute respiratory syndrome (SARS) in South Asia were at their height, Brussels' South Charleroi Airport experienced a 73% rise in passenger traffic to 362,818 in the first three months of 2003. This major increase is attributed to the use of Brussels' South Charleroi Airport by the low-cost carrier Ryanair as its Belgian base on the one hand, and to the launch of new routes and the use of larger aircraft on the other.

Airport planning, all the more when it is strategic, should consider, imagine, and try to quantify the risk of unpredictable events, even the most unthinkable ones. For instance, it is relatively unimaginable that an airport, which is developed as a hub, can lose its home carrier. This can however happen due to circumstances that are totally out of airport planners' control. Since its creation in the 1920's, Sabena had its home base at Brussels National Airport, and represented the major revenue of the airport. When Sabena went bankrupt in November 2001, coupled with City Bird bankruptcy in October 2001, it was a real disaster for the employees of these two airlines (more than 11,000 direct and indirect jobs lost), but also for the airport. The Brussels International Airport Company (BIAC), the airport operator, had to face a 2002 net profit fall to €3 million from €12.7 million the previous year (Reuters, 2003c). The airport handled 14.4 million passengers in 2002, down 26.6 percent from 19.7 million in 2001. All those events that affect the air transport market have intrinsically a certain level of unpredictability. Unpredictability itself represents a risk, positive or negative. The qualification of that risk is no longer sufficient, given the socio-economic stakes involved.

Both traffic demand and capacity are subject to frequent fluctuation. Because of the airport coordination process (EC 2004), slot scheduling and ATFM regulation, delay should normally not originate from a lack of declared capacity. Delay rather originates from sudden and unpredicted capacity changes or, more precisely, from the inaccuracy of planning. Indeed, airports declare capacity 6 months in advance and, for those scheduled airports, the surplus traffic demand in saturated periods is postponed through slot negotiation to quieter periods. However, for a given flight scheduling based on declared capacity, any capacity fluctuation that is uncontrolled, unmanaged, or even worse unknown, results in delay.

Although the examples described above are chosen to illustrate extreme cases of unpredictability, it is recognised that airport planning efficiency continually needs to be enhanced. The quality of airport planning is an issue which is too often disregarded. It is also recognised that changes in capacity require a much more rigorous approach to be efficiently quantified. From a tactical airport planning perspective, this is all the more true as

unpredictable events occur more frequently. Rapid changes in traffic patterns due to last minute notifications of flight cancellations, or capacity changes due to weather forecasts, or technical problems with ATC instruments, are only three examples of unpredictable and frequent events.

Based on a EUROCONTROL performance review, the lack of gate-to-gate transit time predictability costs billions of euros every year (EUROCONTROL, 2005). In order to mitigate unpredictability and satisfy customers, additional time - 'buffer time' – is often built-in to flight schedules by airlines. By doing so, flights may suffer delay and yet be on time if predictable delays are catered for through these buffers. However, the use of buffers is relatively detrimental to ATM cost-effectiveness. For instance, it is estimated that one minute of buffer time for an Airbus A320 is worth €49 per flight. The cost of cutting 5 minutes off 50% of schedules is also estimated at some €1 billion per annum in better use of airline and airport resources. It is recommended to improve predictability through collaborative decision-making, system wide information management, better management of bad weather conditions and better control of take-off time.

It is strongly believed here that part of this cost can be recovered by a better knowledge of capacity fluctuation. In addition to the common operational and intuitive actions, the scientific community could make a significant contribution to improve capacity predictability in terms of modelling and planning.

1.2 Scope and Aims of the Research

The purpose of operating an economic system, whatever it is (airport, telecommunication, production industry, etc), is to maximise returns on investment. To do so, any economic system needs to be operated at the limits of its capacity. As illustrated in Figure 1-1, on one side of the limit, systems are under-operated and latent capacity appears, although the quality of service might be beyond any expectation and no delay occurs. This latent capacity constitutes an obvious lack of revenue and profit. On the other side of the limit, economic systems are over-operated and fully saturated: delay appears and grows exponentially with, consequently, another kind of loss of profit.

Consequently, it is considered that any economic system needs to be operated with an acceptable level of delay in order to be profitable (Janic 2003; Janic 2000). Maximising profit therefore requires finding out the optimum level of operations, i.e. the optimum trade-off

between throughput and quality of service (delay). This challenge really consists in pulling on the capacity rope to the point just before it breaks. The art of planners resides to some extent in the identification of the capacity breaking point in order to maximise the returns on investment.

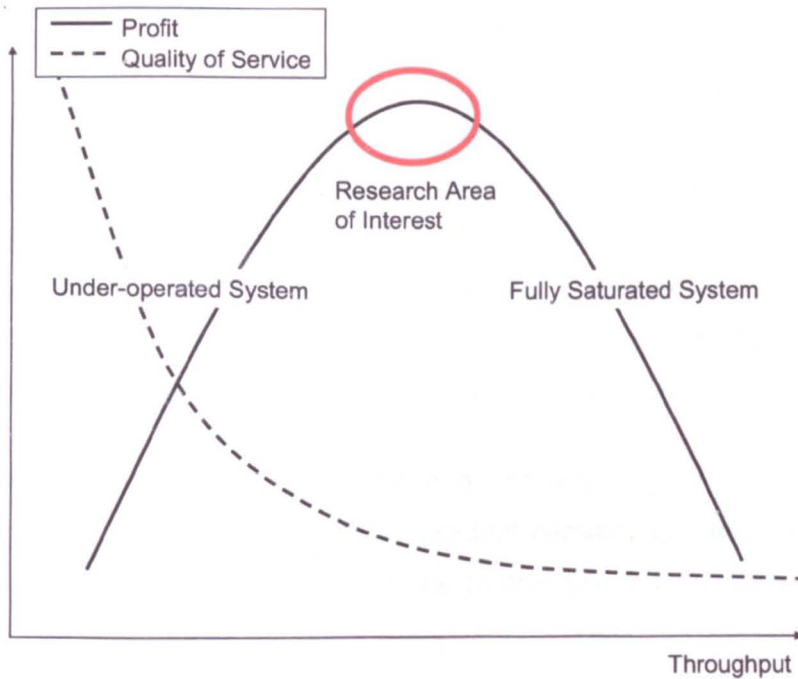


Figure 1-1 – The Challenge of Operating Economic Systems at the Limit of their Capacity

Maximising throughput with an acceptable level of delay requires a detailed knowledge of the breaking point of the rope, i.e. capacity. Because capacity fluctuation is a source of delay, capacity management starts with a better awareness and understanding of capacity dynamics, in order to better mitigate the risks of fluctuation and underlying delay. Based on a sudden operational change, decision-makers can make optimal decisions only if they are *a priori* aware of the impact of this change on capacity. This knowledge is a prerequisite in order to identify efficient mitigation plans to any risk of capacity degradation, so that those plans can be deployed, should such capacity degradation come in an unpredictable way.

The rationale for the research reported in this thesis is based on the three following postulates that any airport business has to face to nowadays.

First, from the perspective of cost-effective airport modelling, fast-time simulation is more appropriate for tactical airport planning rather than strategic airport planning (OPAL, 2003).

Fast-time simulation requires effort-consuming and expensive collection of data that, in essence, are relatively inaccurate at the stage of strategic planning due to long-term horizon unpredictability. Fast-time simulation provides many details that are not particularly irrelevant at that phase of planning. In addition, fast-time simulation requires sharp modelling expertise and usually witnesses a lack of input-output transparency that makes analysing results more complex.

In comparison, and within the scope of strategic airport planning, analytical modelling enables a quick assessment of a wide range of possible scenarios to enhance capacity, and provides airport planners and managers with valuable decision-making assistance in their ability to choose the most promising scenario that best solves their current capacity shortfall, while optimising cost efficiency of airport modelling. Analytical airport modelling has considerable potential for research and development, although it needs to be revisited and adapted to cover all the possible configurations of the whole airport airside and landside.

The second postulate is related to the challenge of any successful airport planner and manager, that is having the vision to identify gradual capacity enhancement steps towards the sustainable most promising solution, in order to alleviate at best capacity shortfall in the short-, medium- and long-term.

Last but not least, runway capacity is often recognised as the limiting factor for airport capacity. Declaring the right runway capacity and maximizing the use of this capacity is of major importance, especially at congested airports. When runway capacity is understated, potential value is lost when it has been estimated that one hourly airport slot is worth several millions euros per annum at a main European hub (EUROCONTROL, 2005). On the other hand, excess demand at those airports where runway capacity is overstated generates poor punctuality and predictability.

In addition to a certain inaccuracy of both strategic and tactical planning, slot scheduling efficiency is not optimised because of a lack of specific guidelines, and because capacity declaration practices do not always consider the factors that are really sensitive. At the airport level, the discrepancy between the declared capacities used on one side for slot scheduling and, on the other side, at the tactical planning level for flow management, can represent either a waste of potential profit (when capacity is under-estimated, latent, even under-declared), or impede local delays (when capacity is over-estimated, even over-declared). The lack of European harmonisation in capacity declaration practices can thus impede the efficiency and stability of slot scheduling at the European scale.

To summarise, the three postulates are as follows:

1. analytical modelling is more appropriate than fast-time simulation for strategic airport planning;
2. gradual steps need to be identified towards a sustainable most promising solution for capacity enhancement;
3. runway capacity is often recognised as the major limiting factor for airport capacity.

Based on these three postulates, this research aims to raise the airport community's awareness of the relative instability of airport capacity and the related impact of that capacity instability on slot scheduling and operations. The purpose of this research is to devise a concept for quantifying the potential fluctuations of capacity, and to design a methodology to assist decision-making in capacity planning and management at airports, with respect to capacity constraints. The objectives of this research are twofold. The first and key objective is to define and formulate three capacity concepts: capacity dynamics, capacity elasticities and capacity stability. Based on the appropriate formulation of runway capacity, these three concepts enable us to quantify which conditions, and to what extent, various factors may affect runway capacity. The second objective will consist of demonstrating the operational usability of the three concepts of capacity dynamics, elasticities and stability through their application in a real case study. The added value of these three concepts will be shown with a decision-making support application: *the airport planning compass*. The airport planning compass enables airport planners to prioritise the different factors that affect capacity based on their real impact. It can assist and guide airport planners and managers in their process of capacity enhancement, as well as in the prioritisation of potential capacity enablers in the scope of both tactical and strategic airport planning.

The proof of the capacity dynamics, elasticities and stability concepts – and, indirectly the output and viability of this research - are demonstrated through an appropriate and specific case study on real operational data provided by a representative European airport, Brussels National Airport. The various models developed in the scope of this research are implemented with an appropriate software application, which is MATLAB.

It is intended that this research will contribute to a better knowledge of capacity fluctuation, and provide the scientific community with a proposal to improve capacity predictability in terms of modelling and planning. Although a cost-benefit analysis remains beyond the scope of this research, it is considered that this research could contribute to recovering

some part, however small, of the €1 billion annual cost of absorbing unpredictability through schedule buffering.

1.3 Research Methodologies

In order to increase the chances of success, great attention is drawn to the selection of a research methodology, which should be as appropriate as possible for the subject of interest. The choice of a research methodology is all the more critical since there exists no methodology that is necessarily superior to others; there just exists more appropriate methodologies than others for a given purpose. And it is up to researchers to find out, and most importantly to customize and fine tune, their own methodology to maximize their chance of leading their research to the most successful end.

As specified by Edwards and Hamson (2001), the essential skills for producing a successful model can be summarized through the following phases:

- I. Identifying the key problem variables and making sensible simplifying assumptions;
- II. Constructing relations between these variables;
- III. Taking measurements and judging the size of quantities;
- IV. Collecting appropriate data and deciding how to use the data; and
- V. Estimating the values of parameters within the formulation that cannot be directly measured or calculated.

Edwards and Hamson's recommendations inspired the methodology used in the scope of the current research, although it has been customized and adapted to the specificities of the subject of interest. Figure 1-2 represents the process flow of the adopted methodology; each stage of this flow is represented by a box. Hereafter, each box is explained with a series of questions and hints which should indicate what is intended.

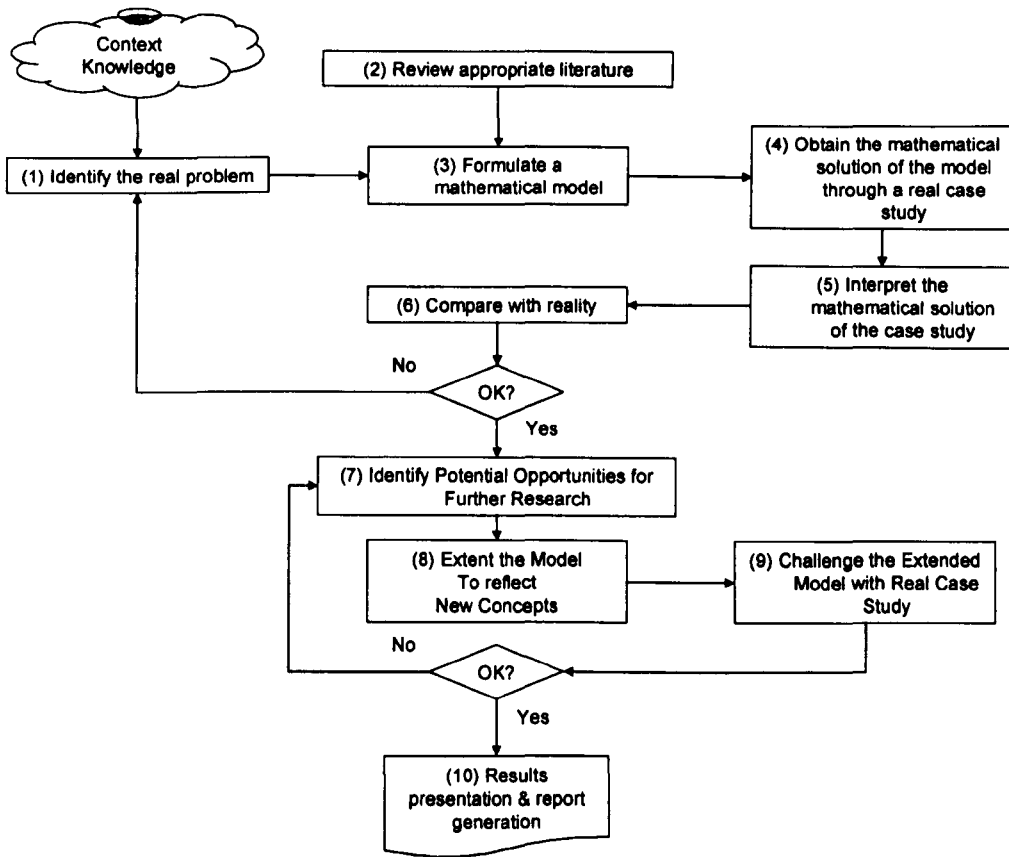


Figure 1-2 –Research Process Flow Chart (Source: Author)

The first phase consists in describing the context in which the problem occurs, and identifying the **real problem** (Box 1) within this context. The result of this enables us to identify the purpose and objectives of the research.

Based on an explicit problem identification, the **mathematical model** (Box 3) can be formulated. It is to be recognised that different models can be formulated for the same initial problem. In order to keep focused on the key issue and not to be overwhelmed by apparent complexity, the simplest model is first used, based on a detailed review of the related **literature** (Box 2), even if this model needs to be refined further to validate and compare with reality.

But prior to any mathematical modelling, drawing up a **comprehensive list of variables** and factors that affect the particular problem is essential to good modelling practice. There is no point in including in the model more variables than are necessary to give an answer with the required amount of accuracy: if any particular variable makes an insignificant contribution to the result when compared to the contributions of other variables, then a wise decision is to

abandon that variable for the benefit of model simplification and transparency. This debate is similar for the expressions and equations which appear in the model.

Whilst referring also to model complexity, this phase also requires stating any **assumption** that it was decided to make. The initial problem has to be cleaned of any kind of secondary aspects that contribute to making the problem more complex, but does not help in finding out a solution to it. Amongst assumptions are also the modelling decisions which are made about the appropriate level of detail to include in the model, about the type of model to be developed (analytical, simulation, aggregated), about modelling the variables as discrete or continuous, about developing stochastic or deterministic models. Assumptions need to be carefully weighed for effect, and the consequences of assumptions are to be sharply analysed. As far as this research is concerned, two key assumptions are made for the purpose of concept clarity (Section 6.3.2) and some consequences are analysed (Section 6.4 and, to some extent, Section 7.1.2).

Having listed the factors and prioritised them according to their expected importance, having reached the right level of model complexity by identifying adequate and reasonable assumptions, the final stage of this phase consists in drawing up the relations and equations connecting the problem variables and factors. This requires and calls for appropriate mathematical skills (for instance, linear and non-linear relations, empirical relations, difference and differential equations, matrices, probability and statistical distributions). In this phase, it is required to take particular care to remember the purpose of the research.

The next phase of the methodology represented in Figure 1-2 consists in obtaining the **mathematical solution** of the model, through a **real case study** (Box 4). In this phase, a hierarchy of relationships between dependent and independent factors is analysed, based on the formulae that were developed in the previous phase. For each pair of dependent-independent variables, the analytical relationships are investigated and analysed in depth (e.g. linear, growing without limit, increasing to a limit, decaying to a limit, simple maximum or maximum followed by tailing off, oscillatory or decaying oscillations). Those factors are examined for information explaining their behaviour. In the behaviour analysis of those factors, the following questions are to be investigated:

- What happens at small or large values of this factor?
- Are there any values of an independent factor for which the dependent factor is null, has a local maximum or minimum?

- What is the range of the domain of the various variables that is relevant for the problem under investigation?

The choice of a single case study is based on a research strategy which is a 'proof of concept'. As a proof of concept, the purpose is indeed to explore in depth analysis, what could not be performed with a set of case studies within the scope of this research. Data consistency can be ensured with one detailed case study rather than with several higher-level case studies. In order to make the case study as realistic as possible, it will need to be based on real operational data.

In addition, computer programs are developed and implemented in order to support the development of the models in the scope of this research. The MATLAB software package is ideal to be used for that purpose (The MathWorks Inc., Natick, MA, USA). MATLAB is a user friendly compiled programming language ideal for modelling and performing fast-prototyping.

The results obtained from the case study are examined and **interpreted** (Box 5). The following questions can be raised during this phase:

- Have the values of the variables got the correct sign and size?
- Do they increase or decrease when they should?
- Should a certain graph be linear, quadratic, and hyperbolic?
- Do we get the expected solution or should some initial conditions or assumptions be changed?

Based on the model developed earlier in Box 3, and supported by the computer program package developed in Box 4, the interpretation of the theoretical solution needs to be challenged through comparison with reality (Box 6). In order to gain confidence in the solution proposed for the identified problem, this theoretical solution needs to be scientifically and operationally validated. Results need to be interpreted in their context to see if they stand up to reality. It is also required to identify the audience which is expected to use and take profit of those results. The user of the modelling output is probably not a scientist, and mathematician in particular; results are to be presented to a non-expert who may not want too much mathematical detail. That is the reason for which the results are to be analysed, discussed and debated with local experts who might not be engineering or scientific experts, but who know the problem through their day-to-day operations experience.

This validation is performed with the intention of answering the following questions:

- Can the results be tested against real data, and are data available, bearing in mind that the best model has very little value if data are too expensive to be collected or simply not available?
- Does the model proposed make sense?
- Do the predictions fit with the real data?
- Has the model fulfilled its purpose?
- Can the model be significantly improved by greater mathematical or simulation sophistication? In other words, do the interim results suggest that more accuracy is required, and does the model need to be improved, and in which way?

Based on the answer to those questions, it might be required to return again to the starting phase of the modelling cycle, related to problem identification (Box 1). Iteration on the modelling cycle might be due to different reasons. Amongst those is the “*manageability*” of the list of variables. The list of variables must be kept to a manageable size. To do so, the variables need to be sorted out by order of influence or relevance, from the more important ones to the least relevant. A relationship diagram will be used for that purpose in the scope of this research, and will be transformed later on into an influence diagram. Any variable that would be erroneously disregarded or underestimated will come to light at the interpretation and validation phases (Boxes 5 and 6), where inadequate representation of reality will appear. It is difficult to judge the importance of a given factor at the outset, and several iterations might be required in the modelling cycle prior reflecting the right sensitivity of a factor. Specific sensitivity analyses on specific factors however enable to fast-track this process, and therefore increase modelling efficiency and likelihood to succeed with operational validation in a minimum of iterations.

A model can, and should, be re-visited after use to see if it can be improved or corrected. The purpose of operational validation is to refine the model used, in order to make it as close as possible to reality, whilst ensuring modelling cost-effectiveness.

As soon as there is an acceptable degree of confidence in the model developed (Box 2), further opportunities for additional research can be identified (Box 7). After validation, the model is indeed judged as being robust enough, and new concepts can be built up above this model used as a basis. In this phase, for the research reported in this thesis, the three

concepts of capacity dynamics, capacity elasticities and stability are developed and synthesized (Box 8). The three concepts are then used in a case study, usually based on the same data than the case study performed in Boxes 4 and 5, in order to analyse their added value in the "real world of operations". This phase (Box 9) also enables us to reiterate the scientific validation of the formulation of the new concepts developed in Box 8. The later phases (Boxes 7, 8 and 9) are very similar to the earlier phases (Boxes 1, 3, 4 and 5); they however have the great merit that the three concepts that will be developed are innovative and, therefore, they cannot be tested with any other realities as nothing similar exists.

Last but not least, the results of the research need to be reported. During this phase, the writing phase of the thesis (Box 10), the following questions are considered:

- What do readers (including internal and external assessors) want to know?
- How much detail is required in the report?
- How can the report be constructed so that the important features are clear and the results stand out?

1.4 Structure of the Thesis

This thesis starts with the current chapter, Chapter 1, which introduces and describes the context of airport capacity in Europe at a high-level, and which sets the context in which this research originated. The objective of this chapter is to introduce the reader to the need for the concept of airport capacity dynamics, elasticities and stability. This chapter also defines the overall aim and objectives, and delimits the scope of the present research as well as the methodology to be used in order to lead this research to a successful end.

The capacity definitions commonly used around the world are reviewed in Chapter 2 which provides a fundamental introduction to runway system capacity analysis. The multiple factors that affect airport capacity, runways in particular, are described with operational examples from several European airports. A pragmatic definition of capacity is proposed, based on the capacity disrupters.

Chapter 3 reviews the research and literature on runway system capacity modelling, and sets up the state-of-the-art on the research published so far with respect to analytical airport modelling. It summarises how the research community have addressed analytical modelling for airport capacity and brings the reader up-to-date regarding this issue. Most importantly,

this chapter identifies those areas that the research community have failed to address so far in terms of analytical modelling of capacity degradation.

Chapter 4 describes the safety rules commonly used as a basis for runway operations, with the purpose of synthesising runway capacity based on an analytical formulation. The multi-dimensional functional relationships between runway capacity and the various factors that affect capacity are extensively analysed, together with their domain of applicability. In order to show the robustness of this analytical formulation of capacity, a case study is presented and analysed at length in Chapter 5. This case study is based on real operational data validated together with one representative European airport, namely Brussels National Airport. The results of the capacity analysis are challenged against an empirical analysis of realised handling capabilities at that airport, as well as through consultations with the major operational experts and airport planners.

The three concepts of capacity dynamics, capacity elasticities and capacity stability are defined and developed in Chapter 6. To proceed with the formulation of these three concepts, a methodology is introduced based on a runway capacity influence diagram. The added values, as well as interpretation, of these three concepts are further described in Chapter 7, which reports a case study on capacity dynamics, elasticities and stability based on the same operational data for the case study in Chapter 5. In this chapter, it is proposed and shown how the airport planning compass application takes full benefit of the synergy and complementary nature of the three concepts, in order to better raise awareness of the major airport actors of the real impact of various capacity disrupters, as well as to prioritise the various options of capacity enhancement action plans in the scope of both strategic and tactical airport planning.

Finally, research conclusions are summarised in Chapter 8, and lessons learnt are reported through a self-evaluation. Further research opportunities and recommendations are consequently proposed.

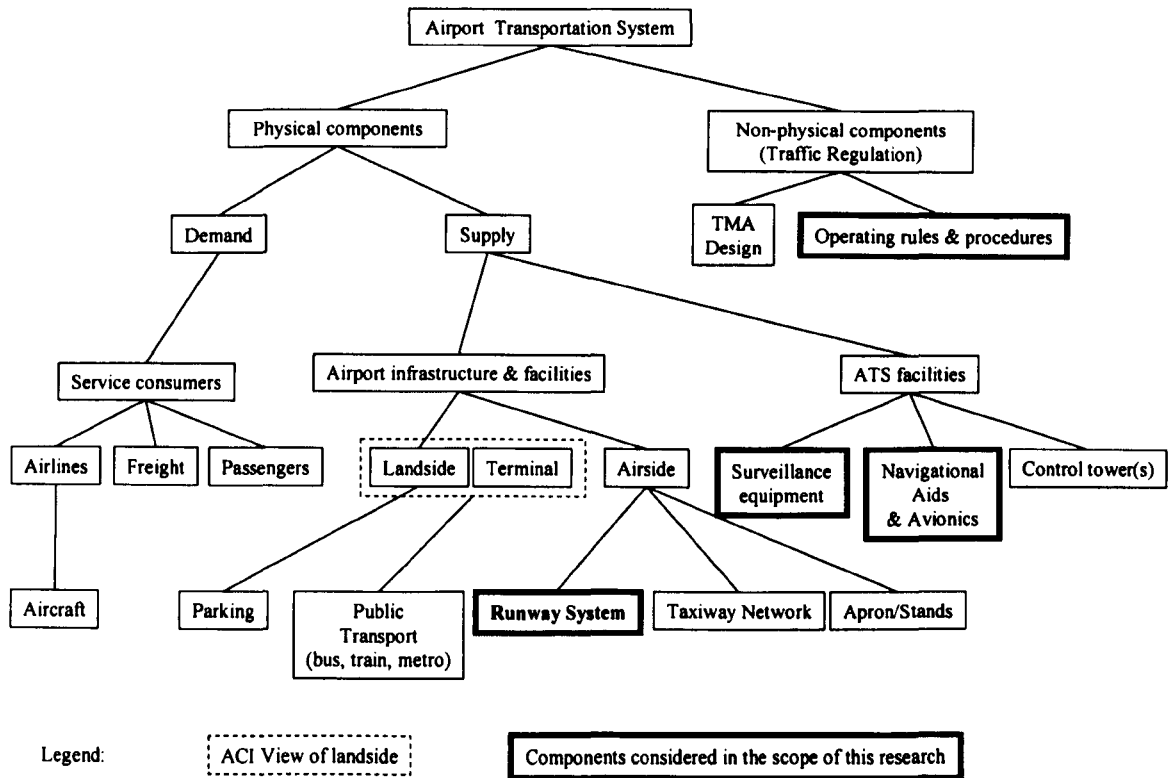


Figure 2-1 – Decomposition of the airport transport system (Source: after Janic, 2000)

Similar to other air transport systems, airports can be broken down into physical and non-physical components. Physical components are represented by demand and supply, while non-physical components are the set of operating rules and procedures regulating the safe and efficient operations of the physical components. To the non-physical components could also be added the design of the terminal manoeuvring area (TMA) that predominantly feeds the airport transport system, especially its runway system.

The demand component is composed of the consumers of the service that can be subdivided into the passengers of various profiles, freight shipments, and aircraft operated by airlines. These aircraft are characterised by various performance and loading capacities. The supply for services is itself composed of the airport infrastructure and facilities, and air traffic service (ATS) components.

Although there is no real boundary between the various components of airport infrastructure, three elements are commonly considered: landside, terminal and airside. The ultimate objective of the landside facilities is to connect the airport to its catchment area, by giving

access to the airport service to any potential consumer of terminal operations. Landside usually includes public transport (e.g. buses) and railway stations, but also facilities for individual passengers (parking slots and taxi stations). Airside includes the runway surface and any manoeuvring/movement area dedicated to aircraft. Airport airside area is composed of the runway system including its adjacent airspace, the taxiway system and the apron areas including the aircraft parking positions (stands). As opposed to landside and terminal - the main users of which are passengers and visitors - the major clients of airport airside are airlines through their aircraft operations.

In this taxonomy, terminals are the mandatory interface between landside and airside. In terms of flows, terminals represent the place where transport service is delivered to arriving, departing, transfer/transit passengers or freight. While referring to the more generic concept of "entity to be moved", a terminal can be defined as the airport component that supports and encompasses all the resource required for the effective, safe and secure substitution of the "entity to be moved" from passengers or freight into aircraft, and vice versa. Terminals include all the equipment required for that transfer, ranging from check-in desks, to departure halls, security, gates, baggage handling, and arrival concourse. In the cargo terminal, similar service is provided to air cargo shipments. At major airports, additional services are provided in the terminals, including commercial activities and business centre operations (organisation of conferences and exhibitions). Originally out of airport core business, those activities nowadays constitute, at some of those airports, the major proportion of airport turnover. In some taxonomies, landside encompasses the terminal. This latter view, represented by dotted lines in Figure 2-1, is commonly used by the Airport Council International (ACI). Coming from the catchment area, ACI considers any equipment and infrastructure upstream of security check as part of landside, whilst any equipment and infrastructure downstream security check is part of airside. In this latter case, the interface between landside and airside is reduced to a security check.

Air Traffic Services (ATS) aim at providing control to the aircraft landing (departing) on (from) the runway system, but also on the manoeuvring area for conflict detection and resolution. The ATS system is composed of surveillance equipment (e.g. radar provision), radio-navigational aids and facilities (e.g. control towers, training centres), and operating rules and procedures. The objective of those operational procedures is to ensure the safe and efficient regulation of air traffic in the vicinity of the airport and on the ground, through the use of time or space separation minima intrinsically dependent on operational conditions (e.g. ATC equipment, weather conditions).

Together with the terminal, the runway system mostly constitutes at airports the most constraining component, because the investment for those facilities is huge. Any development of a new runway or terminal needs to be planned and thought long in advance through a rigorous, open-minded and creative planning process mainly driven by the visionary consideration of aviation business. Regarding the planning for a new runway, the problem is still made all the more complex by environmental impacts (usually on the local neighbourhood) and the decision for such investment is subject to long public inquiry and debates.

The overall scope of any kind of research can be restricted to the strict minimum required to be able to demonstrate as effectively as possible what the research aims at demonstrating – in this case, the added value of the capacity dynamics and stability concepts - without getting lost in the maze of complexity, caused by secondary factors or components that have nothing to do with the research topics. On a more practical side, it also needs to be restricted due to timeframe. In Figure 2-1, the various components considered in the scope of this research are framed in thick-border boxes. Because the runway system is particularly critical from a strategic airport planning point of view, the concept developed in this research will intentionally be limited to the runway only (represented in bold in Figure 2-1). It was Norm Crabtree, of the US FAA, who stated *“The airport runway is the most important mainstream in any town”* (FAA, 2003). However, surveillance equipment, navigational aids and avionics, and operating rules and procedures will also be considered in this research because they might affect runway operations. Although this specific research is intentionally limited for the reasons stated here above, its principles can however be adapted to the other components of the airport transport system.

2.2 Capacity definitions

Janic (2000) defines airport capacity as the capability of the installed aids and equipment to produce a certain volume of services in a given period of time under given conditions. In most publications (cf. Blumstein 1960; Janic and Tomic 1982; Caves and Gosling 1999; FAA 2002), airport capacity is typically defined as *“the maximum number of aircraft operations that an airport can accommodate under given conditions referring to the prevailing operational, economic and environmental influencing factors during a given period of time, which is usually one or quarter of an hour”*. Gilbo (1993) uses a similar concept by defining capacity as *“the maximum number of operations (arrivals and departures) that can be*

performed during a fixed time interval (e.g. 15 minutes or an hour) at a given airport under given conditions such as runway configuration and weather conditions". Although this is relatively beyond the scope of any conceptual consideration, Gilbo (1993) adds further mathematical information by stating that "It (capacity) is calculated as the reciprocal of the mean permissible inter-operation time".

Two concepts of capacity are commonly used while addressing airports: ultimate capacity and practical capacity.

The **ultimate** capacity - also called **unconstrained** capacity - is achieved when, under constant demand, the spacing between flights fits the minimum air traffic flow management (ATFM) separation rules. In such a case, the system is continuously and steadily fed by arrivals or departures, and each flight is served at the minimum time without idle periods. According to Newell (1979), capacity must be uniquely specified by a variety of subsidiary conditions like, for instance, the single runway occupancy rule or the separation minima imposed by a wake vortex constraint. A similar definition of ultimate capacity is used by Janic (2000). Considering an airport as a service provider, capacity reflects the quantity of service that can be produced and delivered during a given period of time and under given conditions. In other words, ultimate capacity is expressed as the maximum number of entities (ATM movements, passengers, bags, and freight shipments) that can be served or accommodated in a given period of time (mostly on an hourly basis) under conditions of constant and continuous demand for service.

In these definitions, ultimate capacity is characterised by the sine qua non condition that is the continuous flow of demand for service, in such a way that the server is fed at any time. No account is taken of level of service which might be reflected by any acceptable level of delay in the system.

Although ultimate capacity is useful in defining the maximum capability of any system, it might often be far away from operational reality. Concerned with the objective of reflecting real airport operations as close as possible, the quantity dimension has necessarily to be complemented by the quality dimension.

Quality is commonly defined as how good or bad something (product or service) is. When considered in management, quality is the level of confidence that a deliverable satisfies relevant quality standards (PMI 2000). When applied to services, quality reflects consumer's satisfaction with products or services consumed. Whilst the term quantity refers to the

volume of output from some production process given the conditions of producing and the period in which it is carried out, the concept of quality addresses the compliance regarding customers' requirements.

There is some obvious relationship between capacity and quality of service, driven by demand fluctuations. In any of the airport components, delay happens whenever demand approaches or exceeds the capacity. In a market in which demand remains relatively constant, quality of service can be improved simply by increasing capacity and reducing by that way the level of service delay. However, when demand fluctuates unpredictably in space and time, capacity provision may be only sufficient to sustain the accommodation of the original demand, and quality of service can decrease proportionally to demand increase. Another intrinsic dependency between capacity and quality of service is driven by the **economics of scale**. The total cost of a system increases with both its capacity to produce and the quality of its product. For instance, the larger the aircraft operated by an airline, or the longer the routes flown, the higher the total cost for that airline. However, the unit cost of service is inversely proportional to the capacity of service production. For instance, the average unit cost per seat-kilometre will decrease if the size of aircraft or flight duration increases.

The concept of **practical** capacity – also called **operational**, **saturation** or **sustainable capacity** – is intrinsically based on a certain level of service. Newell (1979) defines sustained capacity as a maximum average flow that a facility can accommodate over a time period long enough to include a large count (say 100 or more) and which could, in principle, be sustained for an infinitely long time (if one had an arbitrarily large reservoir of aircraft). Practical capacity is also defined as the maximum number of entities that can be served in a given period of time under conditions when the average delay imposed on each entity does not exceed a level prescribed in advance (Hockaday and Kanafani 1974; Horonjeff and McKelvey 1994). The paradox with the definition of operational capacity is that it can be changed – enhanced or reduced - by keeping all the factors affecting ultimate capacity unchanged (infrastructure, ATC equipment or operational procedures), but the acceptable level of delay. By that way, a major European airport increased capacity by 8% during peaks by increasing the acceptable level of delay from 4 to 8 minutes, everything else remaining unchanged.

Capacity is **dynamic** as soon as the timely fluctuation of one or many of its components is taken into consideration. According to Janic (2000), the capacity of any of the airport

components can be expressed by four different measures that represent the capacity attributes. Those attributes are: the service rate of the component under consideration, driven by its physical infrastructure; the dynamic characteristics of demand, such as its dynamic fluctuation over time, its volume and intensity; the profile of entities that form the demand for service; and the quality of service provision, determined by the length of queues and delay for service. The ultimate capacity is determined by the first two capacity attributes only (service rate and demand dynamic characteristics); while practical capacity is in addition dependent on quality of service provided, that is the acceptable level of delay.

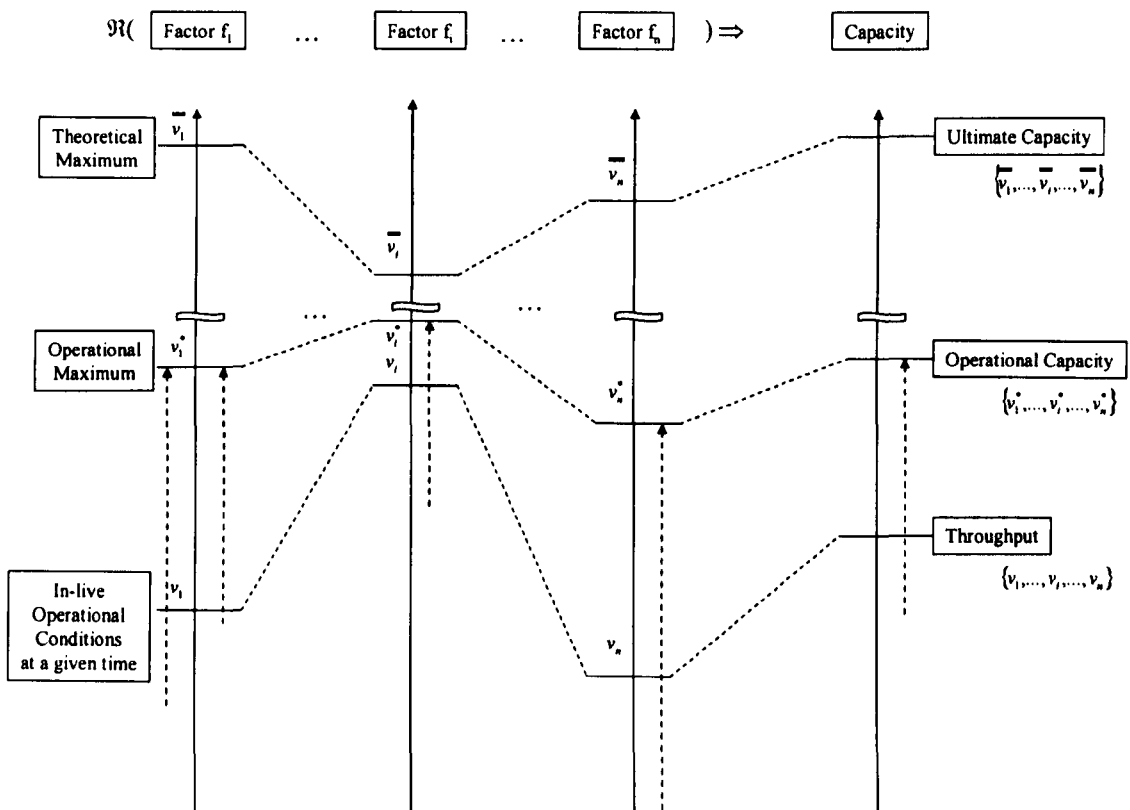
The concepts of **throughput** and capacity are very often confused. Airport throughput is considered as the real volume of traffic accommodated at an airport during a given time interval. In his proposal for an empirical analysis of airport throughput, Gilbo (1993) derives a **maximum practically realisable capacity** that is the practically realisable throughput values that reflect major operational and infrastructural restrictions for the entire range of arrival/departure ratios. The evaluation of this concept of capacity is based on the records of actual accommodated traffic, and for a specific set of conditions (airport state). Gilbo's analysis is definitely valid providing that the 'close to saturation' condition is met, not beyond. This confusion between throughput and capacity is also emphasised by the approach used by most fast-time simulators, which is to derive capacity figures from a throughput-delay curve. Most modellers wrongly believe that simulators provide capacity figures, although mimicking airport operations results in calculated throughput only. Maximum throughput reflects practical capacity for a saturated system only, providing that this condition can be demonstrated. In any other case, these two concepts should be clearly distinguished by airport modellers and airport planners, and this amalgam should not take place.

In conclusion, capacity can be ultimate (unconstrained) or practical (sustainable, saturation or operational), and static or dynamic at the same time. Ultimate capacity refers to the maximum volume or quantity of service that can be provided in ideal conditions, whilst the concept of practical capacity requires an additional dimension that is quality of service, and can be expressed as the maximum throughput at saturation, achieved for an acceptable level of delay.

It is commonly recognised that the airport system is one of the most complex environments in business due to the number of stakeholders involved and related conflicts of interest. The major weakness of the conceptual approach for capacity definition resides in its intrinsic inability to prevent stakeholders from hiding their own interests behind the definitions. The

definitions should be explicit enough in order to leave no place, on one side, for misunderstanding or misinterpretations caused by poor perception and, on the side, for intentional misuse by stakeholders to reflect their personal interests. A factor-based approach for capacity definition could mitigate the risk of both misinterpretation and misuse, as shown in Figure 2-2. As opposed to the conceptual approach, the factor-based approach consists in producing definitions based on the factors that are expected to affect the concept to be defined, capacity to be specific.

Let us assume that capacity is affected by a set of factors, or variables, $\{f_1, \dots, f_i, \dots, f_n\}$. There exists a complex relationship $\mathfrak{R}(f_1, \dots, f_i, \dots, f_n)$ between all those factors leading, in some way or another, to capacity quantification. It is also to be noted that all those factors do have neither the same unit nor the same operational application range. Let \overline{v}_i be the maximum theoretical value for the factor f_i , whilst v_i^* is the maximum operational value of the same factor f_i . Ultimate capacity is then defined as the capacity achieved for the theoretical optimum set of conditions determined by $\{\overline{v}_1, \dots, \overline{v}_i, \dots, \overline{v}_n\}$, whilst operational capacity is determined by the operational optimum set of conditions characterised by the set of variables $\{v_1^*, \dots, v_i^*, \dots, v_n^*\}$. Throughput can be any number of aircraft accommodated during conditions characterised by the set of values $\{v_1, \dots, v_i, \dots, v_n\}$. Although there is no clear boundary between these different concepts of ultimate capacity, operational capacity and throughput, it can be considered that operational capacity is the limit of throughput when saturation is achieved (e.g. when in-trail spacing tends to in-trail separation minima because of traffic density). Ultimate capacity is the limit of operational capacity when operations take place in ideal conditions.



Note: All factors do not necessarily have either the same scale, or the same unit of measurement.

Figure 2-2 – Factor-based Definition and Relationship between Ultimate Capacity, Operational Capacity and Throughput (Source: Author)

When related to a complete system, it is commonly recognised that capacity – should it be ultimate or practical - is determined by the capacity of the weakest component of this system. This assumes that the components of the system under consideration are independent from each other. Concerning airport airside operations, this assumption is considered to be valid as the various components of airport airside are positioned and functionally connected in a serial order (Janic 2000). The weakest component is also identified as the bottleneck of the whole airport system. The ultimate capacity of the airport airside components is to be balanced in order to prevent periodical or permanent bottlenecks in the airport system. Airports can be split into landside, terminal and airside. In the entire reviewed literature dealing with airside capacity (cf. Blumstein 1959; Newell 1979; Ashford and Wright 1992; Gilbo 1993; Terrab and Odoni 1993; Horonjeff and McKelvey 1994; Janic 2000, Stamatopoulos *et al.* 2003) airport airside is composed of the runway system, the taxiway network and the apron areas embedding the parking positions. The runway system includes its adjacent airspace, also called terminal manoeuvring area (TMA). The terminal

manoeuvring area is predominant in the determination of runway system capacity. It is however mostly considered for its potential side effects, as its capacity is dependent on approach control that is related to airspace management rather than airport operations. Although it can temporarily be the cause of delay, the taxiway network is rarely the major cause of ultimate capacity constraint. Airport airside capacity is therefore determined by the weakest of the runway system and the set of parking positions.

Two comments can be expressed regarding system capacity. First, the independency assumption is very much questionable in practice. For instance, the runway capacity for arrivals might be very much affected by the ground traffic circulation efficiency, which is intrinsically linked to the taxiway network. Second, none of the literature considers ATS provision as a component of the airside. Approach controller workload and, to some extent, ground controller workload, become increasingly an issue, especially at the busiest airports, and can therefore become predominant in the assessment of airport airside capacity.

2.3 The Capacity Disrupters

Various factors can affect and, to some extent, disrupt capacity. The word 'factor' includes a number of different entities. It might be *quantifiable*, i.e. numerical value can be assigned to that factor; it might also be *qualitative* when it can be named but not measured numerically. A factor can also be a *relation* between two or more other factors. Quantifiable factors can be classified into variables, parameters and constants. *Constants* have fixed values whilst *parameters* have constant values for a particular problem but can change from problem to problem (for instance, radar separation). *Variables* can be *discrete* (i.e. capable of taking only certain isolate values such as integers) or *continuous* (i.e. capable of taking all values in a real interval). Variables can also be *random* or *deterministic*.

In particular, runway system capacity is dependent on numerous factors, including the volume and time-dependent pattern of traffic demand, the number and configuration of runways, including their inter-dependency, mixture between inbound and outbound traffic flows, aircraft fleet mix pattern, type of radio-navigational facilities and, last but not least, meteorological conditions. In the rest of this Section, those factors that affect capacity at various degrees are referred to as **capacity disrupters**. However, prior to any attempt to list those factors and to analyse their nature, it is necessary to understand the traffic flow towards and from the runway server.

2.3.1 Traffic Flows Towards and From the Runway Server

The process of accommodating aircraft on a runway is illustrated in Figure 2-3, as described by Newell (1979). The source of runway capacity comes from the fact that trips must be focused into a narrow corridor near the airport. For landing aircraft, many flight paths must be squeezed into one common approach path per runway, expanded to the runway itself. As an aircraft approaches a specific runway, it first passes through an **entry fix** located 20-30 miles upstream of the runway threshold. There might be several entry fixes. Efficient approach control aims at squeezing the inbound traffic through the various entry fixes so that they are sequenced on the final approach path with the minimum spacing. Several strategies can be used for sequencing inbound traffic upstream of the entry fixes, like holding, speed control, vectoring or altitude change (especially used when MLS is available). From the entry fix, the aircraft flies along some curved path to the approach gate. The approach gate is the merging point of all the curved paths from all the possible entry fixes. At the approach gate, all the aircraft fly along the intersection of a horizontal and vertical planar radar beam to the runway threshold, called the **outer marker**. The approach gate is located between 6 and 8 NM from the runway threshold. There might be other intersections – **markers** - of horizontal and vertical planar radar beam along the common approach path. The role of the markers is to indicate to pilots how close they are to the runway threshold and guide them regarding their glide angle.

Along the common approach path, aircraft have severe limitations and little flexibility on heading, approach speed, and braking possibilities on the runway. Those parameters might also be dictated by specific operations and human behaviour (both ATC and pilot). All those parameters are in addition accompanied with intrinsic errors in flight direction and aircraft performance. Those errors might not be neglected. In order to avoid "chain collisions", an aircraft must remain sufficiently far from another that it can avoid a collision under all circumstances.

A common question that often comes to mind is how far does the airport modeller have to go into the terminal manoeuvring area (TMA)? Because all aircraft must travel along the same approach path, the one-dimensional line from the approach gate to the runway exit is considered for runway capacity modelling; anything upstream of the approach gate is absolutely obsolete.

After the aircraft has touched down, it may roll to a nearly complete stop before it reaches an exit, or it may turn off on a high-speed exit taxiway. The arrival runway occupancy time is mostly determined by pilot's behaviour and strategy to join its parking position, airframe configuration and weather conditions.

A similar process takes place for departures. Take-off's must also use only one or a few runways and departure paths to predefined departure fixes. All aircraft must follow the same path for a short distance before turning toward one of the several departure fixes. The common departure path is however short compared with the approach path. Similarly, aircraft have little flexibility in acceleration, climb speed and turning radius.

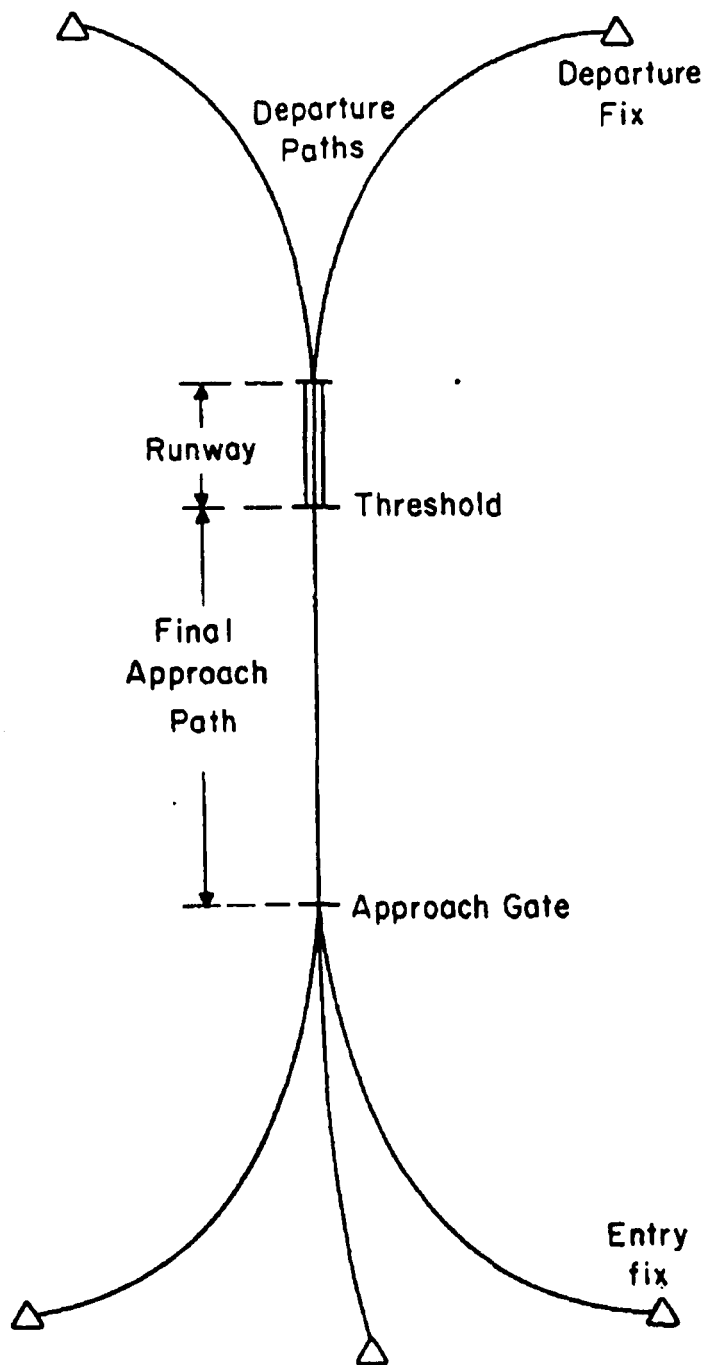


Figure 2-3 – Horizontal projection of flight paths (Source: Newell 1979)

2.3.2 Factors Affecting Runway System Capacity

One of the most important factors affecting capacity is the volume and time-dependent pattern of demand. The traffic demand pattern considerably influences airport capacity allocation over a given time horizon (Janic 2004). The **traffic demand** is composed of

various aircraft types, which are mainly characterised by their maximum take-off weight (MTOW), speed on final approach and initial climb, runway occupancy time, aerodynamic properties and wake vortex in particular. Lift generation is the very essence of the flying capability of all aircraft, but adversely generates wake vortices that might cause turbulence for following aircraft. In order to simplify the work performed by the ATC, while ensuring safe operations, the heterogeneous fleet mix of traffic needs to be aggregated into various representative classes of aircraft. The **fleet mix** is obtained by clustering aircraft into several discrete classes according to their approach speeds and wake vortex inherent to their aerodynamic properties. For that purpose, ICAO PANS-ATM (1996) clusters all aircraft into three major wake vortex groups with respect to their maximum certificated take-off weight. Although several classifications are operationally used, Table 2-1 represents the classification as recommended by ICAO (1996). Beyond ATC requirements, and for modelling purposes, an appropriate level of granularity of aircraft classification results in little loss in accuracy and high computational performance.

The traffic flow analysis reported in Section 2.3.1 emphasises the use of one common path for each type of movement (arrival or departure) on a runway. Any model for runway system capacity should therefore treat the common approach path to the runway together with the runway. As far as inbound traffic is concerned, separation minima must be ensured along the complete approach path. Both the various characteristics of the demanding fleet and the weather conditions dictate the rules of separation minima between both successive movements. The source of minimum **air traffic separation rules** required to fly safely is mainly threefold: radar separation, runway occupancy time and, last but not least, the wake vortex generated by the aerodynamic characteristics of aircraft, mainly driven by their maximum take-off weight. ICAO (1996) recommends the application of distance-based separation minima in instrument meteorological conditions (IMC) between particular aircraft landing sequences.

From a modelling point of view, distance-based separation minima on final approach need to be converted into time-based separation minima. Recent studies on time-based separation also demonstrated that this conversion could help in recovering some proportion of latent capacity at airports. This conversion requires both the distance flown on common approach path as well as the aircraft speed on the portion of the flight. The **length of the common approach path** must be defined from the approach gate to the runway threshold. Because it is mainly dependent on the aircraft stall speed related to its landing configuration at landing weight, it is commonly recognized, and consequently assumed in airport modelling, that

there is no significant difference between the actual speed of an aircraft along the approach path and its speed over the threshold. **Approach speed** can be calculated as the product of the factor 1.3 and the stall speed flown by the aircraft in its landing configuration at its maximum landing weight. This calculation results in the clustering of the aircraft type with respect to five difference ranges of approach speed. The correspondence between distance-based separation minima, aircraft approach speeds and weights is reported in Table 2-1, and permit ATC service providers to decide upon suitable spacing between successive approaches.

Aircraft Type	Aircraft Mix Class	Approach Speed (Knots)	Number of engines	Max. Certificated take-off weight (Kg)	Aircraft Wake Turbulence class	In-trail separation minima (nm)		
						Leading Aircraft		
						Trailing Aircraft		
						L	M	H
Cessna Citation, Dornier 228	A	70-90	Single	≤ 7,000	Light	L	-	4 6
	B	91-120						
ATR42, DC9, A319, A320, B737, B757	C	121-140	Multiple	7,000 < ... < 136,000	Medium	M	-	- 5
A300/340, B747/767/777,	D	141-165		≤ 136,000	Heavy	H	-	- 4
DC10, MD11, L1011	E	Above 165						

Table 2-1 - Aircraft classification and wake vortex separation minima

(Source: ICAO PANS-ATM 1996)

The local **air traffic services provision system** is another operational characteristic of airport airside that affects the capacity of the whole system at various degrees. Determining the appropriate and safe separation minima strongly depends on local radar provision.

ICAO PANS-ATM (1996) recommends 3 nm between successive approaches in the vicinity of an airport, subject to wave vortex separation minima. However, at busy airports, reducing this separation minima to 2.5 nm becomes a common practice; this is increasingly used by the FAA at saturated airports, and also in Europe (e.g. London Gatwick). If no rule applies, for instance in VFR, the practical observed separations could be used. The radar separation minima also vary depending on the radar equipment. For instance, Table 2-2 reports the radar separation minima used in France.

Radar Type	Primary Radar	Classic Secondary Radar	Mono-pulse Secondary Radar
Synthetic Monoradar < 40 NM	3 NM	5 NM	3 NM
Synthetic Monoradar > 40 NM	5 NM	5 NM	5 NM
Synthetic Multiradar	-	8 NM	-

Table 2-2 - Radar Separation Minima

(Source : French DGAC)

Separation minima are supposed to be strictly enforced, not only for safety reasons, but also regarding legal actions in case of potential accident. Any type of **error** relative to the application of ATC rules should be taken into account. Attention should be drawn on the magnitude of errors in arrival time at the entry point to the common approach path (entry gate) as well as on the speed variation of aircraft along the common approach path that could lead to ATC rule violation. A specified probability of violation of the minimum ATC separations should be defined as acceptable. The risk of separation minima violation is mitigated by go-around procedures. However, because controllers have very little flexibility over the landings that are already committed, they usually add their own '**safety**' **buffer** to the enforced in-trail separation minima. Those buffers are expected to cover any potential error in distance or speed measures. For instance, controllers might operate a separation of 3.5 nm where the separation minimum to be enforced is 3 nm. Due to the related impact on capacity, it is paramount to know the distribution of in-trail separation. Whilst the separation minima will produce a theoretical capacity that cannot be exceeded without modifying the

minima (any other factor remaining unchanged), the in-trail separation distribution yields to operational capacity that, by definition, is more realistic.

After touch-down, **runway occupancy times** of various classes of aircraft in the fleet mix are obviously a major input. Their value as well as their magnitude of deviation can result from appropriate statistical analysis.

As far as departures are concerned, separation minima are also applicable in order to cover wake vortex phenomena and the risk of collision it might induce. Departure speed is another factor that usually drives specific separation minima between successive departures. Departure speed is indeed dependent on maximum take-off weight, and successive departures have different climb speed. Therefore separation needs to ensure that faster aircraft do not catch slower ones. Separation minima are also different as the departure track of consecutive take-offs are diverging or not. Airborne separation may vary from 1 to 5 minutes (ICAO PANS-ATM 1996) depending on the departure track and speed.

As opposed to in-trail separation minima that are basically distance-based, inter-departure separation minima are time-based. It is to be noted that separation between arrivals are all larger than between departures. This is justified by the fact that pilot and controller cannot make last minute corrections regarding an aircraft on final approach. Pilot and controllers must allow for any possible event that might occur from the time an aircraft is committed to land until it does land. For instance, if a previous landing aircraft turns off on a high speed exit earlier than anticipated, the following approach is not in a position to take advantage of it.

Another major factor affecting runway system capacity is the **airport layout and geometry**, characterised by the number, directions and length of runways. The appropriate type and location of runway entries and, more importantly, runway exits are predominant for runway occupancy time.

For those airports whose infrastructure includes several runways, the appropriate choice of runway configuration is paramount in capacity management. The decision for a given runway configuration is driven by several criteria, the first one being safety. The choice of appropriate runway configuration is determined by aerodynamic performance of aeroplanes and prevailing wind direction and intensity. The two conditions for a given configuration to meet the safety standards are that tail wind does not exceed 15 knots and cross wind must be maintained below 30 knots. Other criteria can influence the decision for special runway

configuration. Environment is increasingly decisive in this choice. **Noise abatement** procedures are more and more often enforced by airport authorities as a policy of neighbourhood appeasement, with the adverse implication that noise abatement usually contributes to capacity decreases. At Brussels National Airport, for instance, politicians voted for a rule that regulates the use of some runways, in order to reduce noise constraints, keep the airport vicinity as quiet as possible and balance the impact on the two concerned regions of the federated country. In good visibility and no wind conditions, the air navigation service provider can choose the runway configuration depending upon a noise distribution plan. This latter case is no doubt driven by regional and national politics. Although beyond the scope of the present research, it is to be mentioned that high danger might emerge as soon as the political reasons gain in importance regarding to aerodynamics rules and underlying safety. Indeed, it happened that the proposals resulting from political considerations were questioned and challenged by the operational experts (air traffic service and pilots) from a safety perspective.

In a multiple-runway layout, two parallel runways need to be separated by more than 1035 m and less than 1310 m, from centre line to centre line, to be considered as dependent for instrument flight rules (IFR) operations (ICAO 2001)¹. Segregated operations may be conducted on parallel runways provided that the two runways are separated by 760 m minimum from centre line to centre line. When two parallel runways are separated by less than that distance, they must be operated as one single runway (e.g. Istanbul Atatürk Airport, where runways 18R/36L and 18L/36R are separated by 210 m only). When runways are dependent, both longitudinal and transverse spacing of approach and departure paths are limited for safety reason. Error margins for possible errors in flight speed and direction, or in technological equipment for landing assistance, have to be taken into consideration. In order to mitigate the risk of human and technological errors, and ensure safety, the following parameters are to be considered when several runways are inter-dependent:

- The **diagonal separation**, which is the separation minima between two successive approaches on two dependent parallel runways. This diagonal separation minima varies between 2 and 1.5 nm depending on airport equipment;
- The runway visibility minima for simultaneous landings to converging runways;

¹ Paragraphs 6.7.3.2.1, 6.7.3.5.1, 8.7.4.4.1.b

- The runway visibility minima to release a departure on one runway while the other runway is used of approaches (in converging and crossing configurations);
- The distance between parallel runways for ***independent parallel approaches***; this prohibits instrument landing systems (ILS) from interfering with each other. The current distance recommended by ICAO (2001)² is between 1035 m and 1310 m for instrument flight rules (IFR) operations.

Other factors affecting capacity of a runway system are the ***ATC operational tactics***. At single-runway airports, or when closely-spaced parallel runways do not permit independent arrivals and departures, those tactics consist of sequencing inbound and outbound traffic while maximizing capacity.

Last but not least, the ***meteorological conditions*** are, without doubt, the more dynamic and certainly the most unpredictable factor influencing airport capacity and delays in a major way, as emphasised by Krollova (2004). The lack of accuracy of weather forecasts undoubtedly constitutes a real cause of delay. According to EUROCONTROL (2005), around 40% of airport ATFM delays and 10% of en-route delays are initially due to weather. Current operational practice at Amsterdam Schiphol Airport shows that the forecast on extreme weather conditions is accurate for only 30% of the time. This results in 10 to 15 situations a year where flow restrictions are not adapted to the actual weather conditions; consequently capacity cannot be used to its full potential.

According to weather conditions prevailing in the airspace and vicinity of the airport, the airport operations might be IMC (Instrumental Methodological Conditions) or VMC (Visual Meteorological Conditions). The safe separation rules applied by the ATC to accommodate the traffic demand are dictated by those weather conditions (ICAO 1996). According to Terrab (1993), the capacity of airports is a probabilistic quantity and is relatively difficult to predict in marginal weather conditions. Because weather forecast is subject to large errors, even a couple of hours in advance, capacity might be difficult to predict. However, this problem can be considered as part of risk management, in which the potential risk for wrong prediction must be identified, quantified, and coupled to some mitigation plan. To help mitigation, the ***capacity coverage curve*** enables the influence of weather conditions on the

² Paragraph 6.7.3.2.1.a.1

airport capacity to be reported. This curve describes *“the maximum hourly capacity available at an airport as the percentage of time during any period of time”* (e.g. a day, a year, ...).

Table 2-3 illustrates an example of impact due to weather conditions at Boston Logan Airport, US.

Percent of time per annum (%)	Hourly capacity (mvt/hr)	Weather conditions
0 – 40	126	Good VFR; Ceiling > 2500 ft; Visibility > 5 nm
40 – 50	110	
50 – 60	108	
60 – 85	78	
85 – 88	68	
88 – 90	64	
90 – 98	55	
98 – 100	0	Airport close due to Poor IFR; Ceiling 200-500 ft; Visibility 0-2.5 nm; snow

Table 2-3 – Capacity coverage curve for Boston Logan Airport, 1992

(extracted from Janic (2000))

Figure 2-4 represents a summary of the factors that are commonly recognised as capacity disrupters.

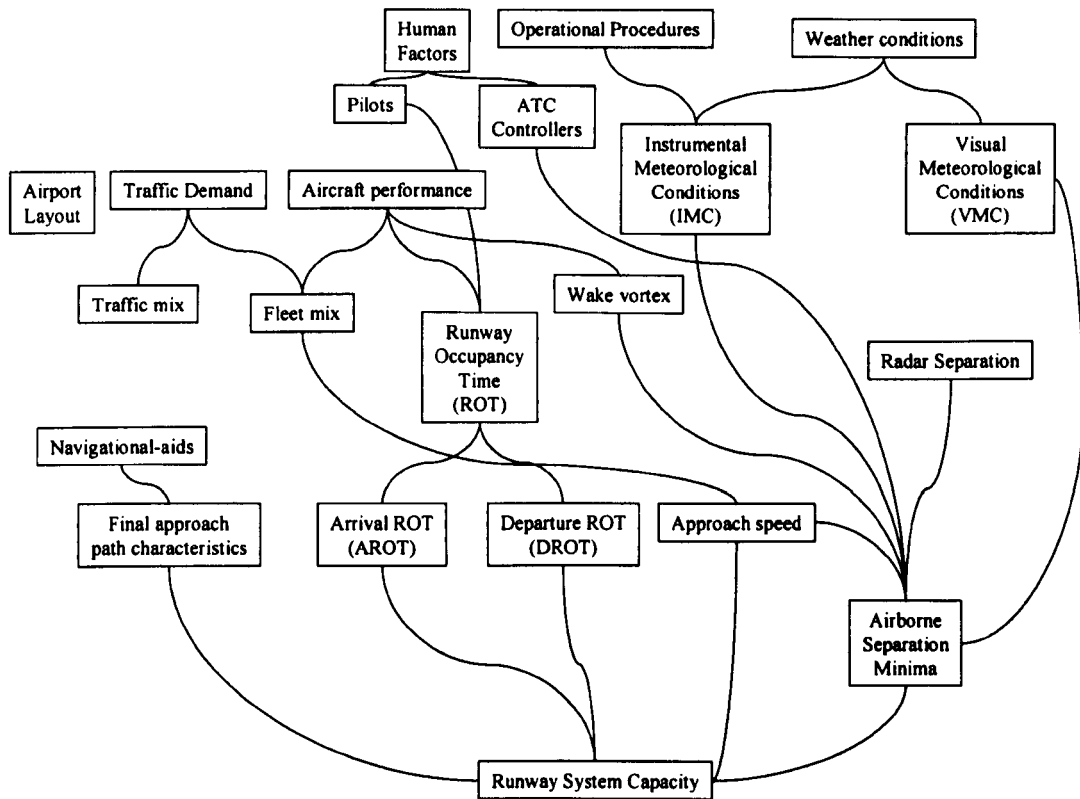


Figure 2-4 – Factors affecting runway system capacity

2.3.3 Factor-based Taxonomy

As reported in Section 2.3.2, runway system capacity is dependent on numerous factors. Although there is no definite rule to classify the various factors affecting a system, those factors have in essence typical characteristics. Three characteristics are considered as primordial in the scope of this research: the *static* factors are constant over time (e.g. infrastructure) while the *dynamic* ones change frequently (e.g. fleet mix); some factors are *endogenous* when they can be controlled within the system under consideration (e.g. spacing between successive movements), while others are *exogenous* when they are external and out-of-control of the investigated system although they might affect it (e.g.

weather conditions); and last, factors might be relatively *heterogeneous* (e.g. aircraft type) when it consists of many different types of instances with different characteristics, whilst others are *homogeneous* (e.g. radar provision).

Due to the investment required, the airport layout and geometry - characterised by the number, directions and length of runways - constitutes the major constraint affecting runway system capacity. The runway instrumentation is also relatively fixed over time (De Neufville and Odoni 2003). In Europe, the runway infrastructure can also be seen as a constraint since strong environmental pressures make difficult the enterprise for new runways. The factor-based dynamics is intrinsically dependent on the time horizon during which this factor can keep a stable state. The shorter the time horizon, the more dynamic the factor will be, and hence, the more difficult capacity planning will be. The characteristics of the local air traffic demand for airport access and services constitutes, after weather conditions, the most dynamic factor influencing airport capacity. Those two dynamic factors can however be distinguished by their time horizon of influence. Traffic demand is especially dynamic at those airports accommodating charter flights or low-cost carriers. The core business of those categories of aircraft operators, and their relative success, consists in reacting as quickly as possible to instantaneous and very short-term market characteristics. Airports accommodating business city-pairs are less subject to traffic demand dynamics, and are usually regulated every six months at the time of IATA slot scheduling meetings. In order to minimize delay and optimise air traffic and capacity management, those airports are co-ordinated or scheduled-facilitated (EC 2004).

The traffic demand is composed of heterogeneous aircraft types, which can be characterised by their maximum take-off weight (MTOW), aerodynamic properties, speed on final approach and initial climb, runway occupancy time, etc. In order to simplify the work performed by the ATC, while ensuring safe operations, the heterogeneous fleet mix of traffic needs to be aggregated into various representative classes of aircraft.

Beyond those endogenous factors which have a direct impact on runway system capacity, airport capacity can be constrained by more exogenous factors, like airspace design (SID's and STAR's) and congestion (sector loading and related ATC workload), especially terminal airspace (TMA), as well as human factors (ATC workload based on local experience, staff scheduling and operational procedures).

One primordial measure of the intrinsic quality of planning definitely lies in the accuracy of predictability. There exists an intrinsic relationship between factor-based dynamics and the

quality of the airport planning process, shown in Figure 2-5. The quantification of the accuracy of predictability is certainly not a straightforward issue, and no research on this issue is reported in current literature. Although this is not the crux of this research, some development of this issue will be proposed in the scope of this thesis.

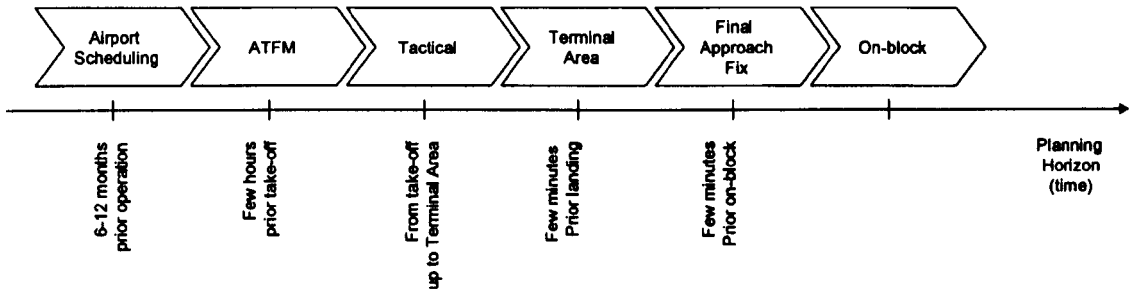


Figure 2-5 – Planning time horizon

2.4 Conclusion

The core airport components have been outlined in this Chapter, in order to define the scope of this specific research, which is runway capacity. The various definitions of capacity have also been reviewed. The variety of these definitions is such that airport planners and modellers often do not know which way to turn with regards to the use of terminology in a consistent way. It can be concluded that a number of definitions give rise to possible misunderstandings or misinterpretations caused by poor perception. It was also recognised that the choice of a given definition of the same terminology originates sometimes from the intention to reflect the interests of key stakeholders.

The multiple factors that affect airport capacity, runways in particular, have been outlined and discussed with operational examples from several European airports. In order to mitigate the risk of misunderstanding or misinterpretation of the capacity concept, a more pragmatic definition, based on the influencing factors of capacity, has been proposed.

Chapter 3 - Review of Research and Literature on Runway System Capacity Modelling

This chapter considers the state-of-the-art of research regarding analytical airport modelling. The objective is to summarise how the research community have addressed analytical modelling for airport capacity and to bring the reader up-to-date regarding this issue. Most importantly, this Chapter aims at identifying those areas that the same research community have failed to address so far in terms of analytical airport modelling and capacity planning. It aims at setting a robust basis for developing an analytical approach for runway system capacity analysis and demonstrating the concept of airport stability, in the following sections of this overall research.

In this Chapter, the key literature is reviewed and analysed in depth (Blumstein 1959; Newell 1979; Gilbo 1993; Terrab and Odoni 1993; Janic 2000; Janic 2004; Stamatopoulos *et al.* 2003, Pitfield *et al.* 1998). More general literature is also reviewed (Ashford and Wright 1992; Horonjeff and McKelvey 1994). The review of literature emphasises the potential differences of newly identified analytical approaches, and analyses their strengths and weaknesses.

Both capacity analysis and optimisation of capacity allocation are used by airport managers as an effective aid to decision-making. Alternative management strategies can be investigated, even quantified, by varying the parameters that affect airport operations through either sensitivity analysis or 'what-if' scenarios. Strategic airport planning requires airport managers to evaluate various alternatives and choose the solution that best fits their current and future requirements and expectations, based on the major business driver, namely returns on investment.

Many researchers have conducted analytical modelling for the purpose of airport capacity analysis. For many years, analytical modelling has been considered by academic institutions as an imperative basis for education in strategic airport planning. Due to its relatively low operational cost and adequate level of detail for strategic airport planning, analytical modelling has been commonly considered as appropriate at that level of planning. It is also increasingly recognised as the most cost-effective approach for that purpose. For some years, profit-making entities have recognised the added value of analytical modelling for airport capacity, and made it a key issue, by developing analytical functionalities upstream

for their airport capacity analysis tools and simulators. Some European CAA's have developed their own tool (e.g. MACAO in France, PICAP in Spain), whilst the European Organisation for the Safety of Air Navigation (EUROCONTROL) opted in 1999 for an analytical approach in the implementation of its Commonly Agreed Methodology for Airport airside Capacity Analysis (CAMACA).

However, one impact of these intensive research and related software developments is that potential users of analytical approaches admit that they no longer know to which analytical model they should devote themselves for the purpose of strategic airport planning. Although it is recognised that harmonisation of this type of research is an utopianism, according to Donohue (personal communication, 24 November 2004) and Zografos (personal communication, 10 June 2005), the risk of this apparent overload of formulation and potential divergence requires getting the story straight about this issue. There is therefore a need to review the research related to analytical modelling for airport capacity in order to come up with the 'most' promising analytical approach – should this exist - for airport airside capacity analysis in the scope of strategic airport planning.

3.1 History of Analytical Airport Capacity Analysis and Optimisation

Airport capacity can be estimated and simulated using a wide range of more or less effective methods. The history of air traffic flow management analysis and optimisation started in the late 1950's with 1st-generation models – or rather methods - in which airport capacity was expressed by two or more separate, independent and high-level values, one for arrival capacity, another for departure capacity, and sometimes for mixed mode of operations composed of successive arrival/departure sequences (FAA, 1969; FAA, 1995).

The major work was done by the Airborne Instrument Laboratory, in the US, under contract with the FAA (Airborne Instrument Laboratories, 1963a & b). The resulting capacity handbook described the maximum number of possible aircraft movements that could be accommodated for various runway configurations, and the delays that were expected to be experienced at various levels of demand. This handbook however fell short of expectation, because the predicted capacities frequently fell well below existing throughput and the predicted delays were even worse (Newell, 1979). A revised handbook was undertaken, based on refinement of capacity modelling (FAA, 1995).

Considering only one capacity value probably results from the fact that, for most planning and operational purposes, capacity is assumed to be relatively stable during some given period (Janic, 2000). Runway capacity is often specified as the reciprocal of the minimum permissible time spacing between successive movements, landings or departures. Several authors, including Pearcey (1948) and Galliher and Wheeler (1958), considered the landing service rate as a constant in their early queuing studies of delays.

At many airports, those independent values were determined by ATFM operators either by using the rule of thumb, or by simply counting the number of ATM movements accommodated at a specific airport during a given time interval. This process was sometimes made easier through the use of simple calculation spreadsheets. In the best case, those two values can vary for given airport states defined by specific runway configurations and weather conditions, but remain unchanged throughout the life cycle of those airport states.

The advantages of these 1st-generation models definitely reside in the fact that they were quite simple to use and did not require any expertise in terms of airport modelling and/or planning. 1st-generation models aimed at producing charts and calculations for the purpose of airport operators and users. The single expertise required by those people was the ability to look up numbers in those charts and calculations, the most commonly known being the FAA handbook (FAA, 1995). They were also convenient – and mostly all the more dangerous – to compare airports based on volume of traffic. They indeed possessed the inherent defect of disregarding the various factors and conditions affecting the volume of services provided during a period of time under consideration (Janic, 2000). As predicted by Newell (1979), the calculation resulting from 1st-generation models became obsolete, due to the dynamic aspect of airport capacity. Because of this reason, and because 1st-generation models mostly provided independent values that were relatively inaccurate and short of rigour, it was relatively difficult to use 1st-generation methods for the purpose of strategic airport planning. The airport community realised that airport planning and modelling required more insightful expertise to lead to the most promising planning option and optimised returns on investment. Those two reasons prepared the ground for 2nd-generation airport capacity models.

In 2nd-generation models, airports are considered as service providers where the customers (e.g. passengers, aircraft, and freight shipments) receive a service during a given period of time under given conditions. In those 2nd-generation models, arrival and departure capacity

were specifically treated as interdependent processes. Newell (1979) is one of the earliest pieces of research on the concept of interdependency between arrival and departure capacity, conditioned by the ATFM separation rules, mixture of inbound and outbound demand, aircraft fleet mix, and runway configuration (Janic, 2004). The traffic mix dimension, characterised by the ratio between inbound and outbound traffic, was quickly added to the general consideration of the capacity modelling issue. The relationship between arrival and departure capacities has been extensively addressed by Swedish (1981). In 2nd-generation models, arrival and departure capacities are connected with each other through a convex and non-linear functional relationship (Newel, 1979; Swedish, 1981). This convex piecewise-linear function is based on the five following hypothetical conditions: departure only, mixed mode of operations with pre-emptive priority to departures, balanced arrival/departure, mixed mode of operations with pre-emptive priority to arrivals, and arrivals only. Any intermediate value between those five hypothetical conditions, when required, is obtained through linear extrapolation.

Unlike 1st-generation methods, the 2nd-generation models were specifically designed to take the airport system dynamics into consideration, and to be used for sensitivity analyses and 'what-if' scenarios, subject to the changes of the factors influencing airport capacity. The classical representation of the capacity envelope is based on assumptions regarding the distribution functions of stochastic variables (Blumstein, 1960; Harris, 1972; Hockaday *et al.*, 1974; Tomic *et al.*, 1976; Newel, 1979; Swedish, 1981; Hamzawi, 1992). The reliability of the results directly depends upon the quality and accuracy of the *a priori* information required to assess those distribution functions. The variation of capacity resulting from the stochastic characteristics of its determinant variables is also analysed through appropriate sensitivity analyses. The disadvantage of 2nd-generation methods compared to the 1st-generation calculation-based methods resides in their inherent fondness for appropriate data collection, calibration effort, and operational validation for further use in operations and strategic airport planning.

The level of details addressed by a model defines the macroscopic (microscopic) characteristic of that model. This characteristic is mainly dependent on the number of variables and parameters considered by the model, as well as the type of assumptions which it is based on. Although this does not constitute a rule, 1st-generation approaches are usually more macroscopic than 2nd-generation ones. The extreme level of microscopic analysis is achieved with fast-time simulators (SIMMOD, TAAM, and Airport Machine) that mimic operations whilst taking a great number of variables into consideration (OPAL, 2003).

An intermediate approach, located between 1st and 2nd generation, is proposed by Gilbo (1993). In his determination of practically realisable capacity, Gilbo proposes an empirical approach for macroscopic airport capacity assessment, and demonstrates its validity at some busy US airports. The US Federal Aviation Administration (FAA, 2002) regularly updates these envelopes for the 29 busiest US airports (Janic, 2004).

The classical and major methods proposed in the literature are reviewed in the next Sections with their advantages and disadvantages.

3.2 An empirical approach to macroscopic airport capacity assessment

It is quite well established that arrival and departure operations are interdependent processes and are connected with each other through a convex and non linear functional relationship (Gilbo, 1993; Janic 2004). In his paper, Gilbo (1993) provides capacity figures for the full arrival/departure ratio spectrum, for various runway configurations and weather conditions.

To do so, real observed data is collected on the number of arrivals and departures at airports during a fixed time interval (e.g. one hour, 15 minutes) over a sufficiently long period of time. The frequency of each couple (arrival, departure) is plotted. Gilbo's methodology is based on the assumption that the observed peak arrival and departure counts during a given period of time reflect the performance of the airport under consideration near capacity level. The recorded (arrival, departure) peaks need to be representative from a statistical perspective; the records that occur occasionally and, consequently, are not realistic, need to be rejected. The contour of the (arrival, departure) peaks are then calculated and assimilated to capacity curves, also called envelopes. Figure 3-1 represents such an envelope of what Gilbo (1993) defines as the *practically realisable airport capacity* concept, in order to formulate an approach to the operational optimisation of airport capacity allocation. This methodology will be further applied in the case study reported in Chapter 5.

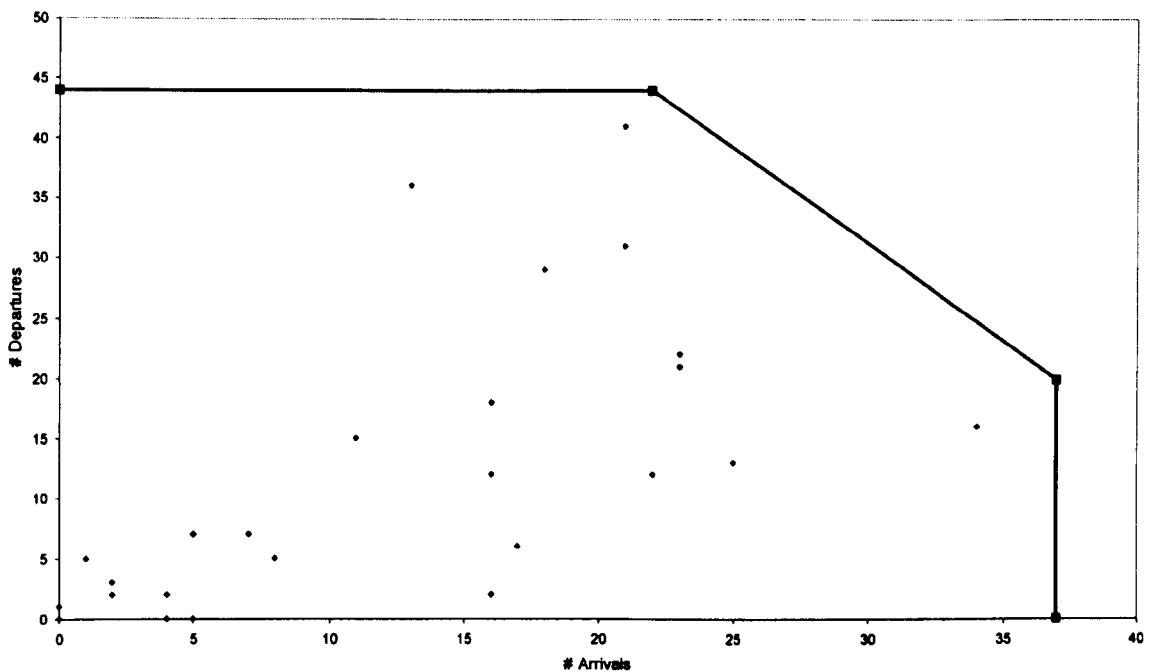


Figure 3-1 – Gilbo's (1993) representation of his Practically Realisable Airport Capacity Concept

Gilbo's approach has several and non negligible advantages. Amongst them, a major one resides in its ability to quickly determine the macroscopic capability of existing airports with no need to collect detailed data in order to assess capacity for any of its components, but to use global airport throughput records. Whilst referring to Figure 2-1, Gilbo's methodology enables the performance of the airport system to be evaluated without having to focus on anyone of its sub-components. This macroscopic concept focuses on the entire level of airport activity and encompasses any kind of constraint and restriction to airport operations, should it be on landside, terminal or airside. The dynamic use of this approach provides time-varying capacity profiles that can reflect the dynamics of traffic demand and the various conditions that exist at airports, illustrated by various airport-states.

2nd-generation models for capacity assessment are defined by a maximum of five fixed constants predefined by runway operational strategies (departure only, mixed mode of operations with pre-emptive priority to departures, balanced arrival/departure, mixed mode of operations with pre-emptive priority to arrivals, and arrivals only). The capacity curve covering the full range of arrival/departure ratios is obtained through linear extrapolation between those five calculated points. In comparison with 2nd-generation models, the

empirical analysis developed by Gilbo enables several arrival/departure pairs to be added to the capacity curve, enabling a more accurate capacity estimate over the full range of arrival/departure ratios. The resulting set of realistic capacity curves for each runway configuration and weather condition represents detailed information on the operational limits of the airport.

Gilbo (1993) proposed the combination of analytical and empirical methods in order to get more reliable and realistic estimates of airport capacity. The empirical analysis of historical traffic records has revealed its usefulness in calibrating the analytical models for capacity assessment; it significantly contributes in enhancing confidence of the baseline scenario that is used as a basis for the benefit analysis of projected strategic airport planning options, through various sensitivity analyses and "what-if's" scenarios.

Gilbo's concept of *practically realisable capacity* was widely used from 1989 to 1992 for those US airports that were characterised by high traffic volume and high demand/capacity ratio. It shows good correspondence with the Engineered Performance Standards (EPS) from the FAA for critical airports, assuming that the estimated capacity curves represent operations at or near practical airport capacities.

However, Gilbo's approach has also severe disadvantages or, at least, warnings that airport analysts and planners should be aware of in order to avoid any blind use of the methodology. Gilbo's concept of "*practically realisable capacity*" actually reflects the maximum practically realisable throughput of existing airports, depending on the records of actual accommodated traffic, and for specific sets of conditions (airport states). The capacity of a system is indeed fully independent on the demanding traffic volume which that system is able to accommodate, if any other factor remains unchanged, including fleet and traffic mix. Therefore, discussing capacity for an empirical analysis of observed accommodated demand might be misleading and has to be considered with great caution.

The capacity assessment based on empirical analysis of real observed data is valid only when it is assumed that, during a given period of time, the observed peak arrival and departure records reflect the airport performance at saturation, i.e. at or near capacity level (Gilbo, 1993). For congested airports only, it is reasonable to assume that the historical peak data reflects the maximum operational capabilities and, hence, can be useful for capacity estimation. Significant delay records indicate that airports operate close to or at their operational limits. The delay experienced by an airport under certain conditions and during peak hours can therefore represent a good indication that Gilbo's '*close-to-saturation*'

assumption is valid for this same set of operational conditions. To be valid, the capacity values resulting from empirical analysis must therefore be complemented by delay records demonstrating the validity of the '*close-to-saturation*' assumption. At non-congested airports, Gilbo's practically realisable capacity concept cannot reflect airport capacity, due to lack of demand and resulting latent capacity.

A major difficulty of the empirical data analysis lies in the identification of their relative robustness thwarted by the possible extremes in the observed data. These extremes – also called *outliers* - can be caused either by errors in the historical data collection process³ or, real but rare, occurrences of airport operations beyond the normal operational capacity limits of the airport for a short period of time⁴ (Gilbo, 1993). The robustness of the practically realisable capacity curves, and its ability to reflect reality, are directly dependent on their non-sensitivity to outliers. Hence, the identification of appropriate and efficient rejection criteria for the extreme observations, as well as the related rejection algorithms, are paramount and relatively critical for the confidence in the results.

The *practically realisable capacity* estimate is based on empirical analysis of statistical data. Beyond the scope of the practically realisable capacity concept, several important issues should be addressed in further research, such as the minimum amount of observed data required in order to ensure the significance and confidence of the sample characteristics, accuracy of the data collected, stability of the related capacity estimates, and the sensitivity of those estimates. Also not addressed by Gilbo (1993), other than through the identification of airport states, is the seasonal impact of observed data.

The empirical approach based on airport throughput focuses at the airport level and not to any of its individual components, as opposed to analytical models for airport capacity that relate, most of the time, to the runway system. Because of this scope differential, the practically realisable capacity provided by an empirical approach (Gilbo, 1993) and the mathematical runway system capacity calculated with an analytical model (Janic, 2004)

³ For instance, time events might be unintentionally and occasionally omitted by the collectors.

⁴ For instance, unusual pilot behaviour causing abnormally short or long runway occupancy time might result in low practically realizable capacity during the observed period of time. On the other extreme, practically realizable capacity beyond normal operational capacity limits can be caused by abnormal fleet mix favourable to extreme throughput.

might substantially differ, even at critical airports in terms of demand/capacity ratio, when the weakest and most constraining airport component is not the runway system.

Last but not least, the determination of the capacity envelope through the empirical approach (Gilbo, 1993) is based on historical and therefore post-operational flight data. It was demonstrated to be relevant in the scope of strategic air traffic management and related capacity allocation at existing airports. It can, nevertheless, not be used for the purpose of strategic airport planning - simply due to unavailability of flight records for pre-operational and hypothetical capacity enhancement options at existing or new airports.

In brief, Gilbo's (1993) methodology tells you how you perform, but does not tell you to what extent, and most importantly how, you can better perform.

3.3 Formulation and Representation of Landing Capacity on a Single-runway

Based on experience in the US (FAA, 2002) as well as in Europe, it is commonly recognised that the major limitation to runway system capacity is the rate at which airports can accommodate inbound traffic.

Blumstein (1959) develops an expression to determine the mean landing service rate – and corresponding landing capacity - of a single runway, in IFR, as a function of the mix of aircraft landing at the runway, the parameters of the aircraft speed distribution, a minimum space separation at the beginning of a common approach glide path, the length of this common glide path, and a minimum time separation at the runway (runway occupancy time). In this way, Blumstein (1959) provides an indication of the relative significance of the parameters affecting arrival capacity.

The rationale of the minimum distance separation at the gate is to prevent collision between successive aircraft on final approach. This minimum distance separation is dictated by maximum position uncertainty of the aircraft on final approach and system response times. The distance between the approach entry gate and the runway threshold is dictated by the distance an aircraft requires to stabilise on the final approach path.

The conclusion from Blumstein (1959) is twofold. First, the improvement in the landing rate can be achieved by reducing the separation at the beginning of the common path, and little is gained by reducing only arrival runway occupancy time. Blumstein (1959) demonstrates that there is little advantage to be gained for runway landing capacity in IFR by a reduction in

arrival runway occupancy time by techniques such as fast turn-off. He states *“Only if the gate separation can be reduced sufficiently below 2 miles can a major contribution result from a reduction in runway occupancy time”*. This statement is however to be kept within the context of arrivals only; other considerations, such as increased take-off rate, may weigh in favour of decreasing arrival runway occupancy times.

Since the separation at the approach entry gate is largely dictated by errors in knowledge of aircraft position, there are two ways of improvement: first by ensuring more precise position information by higher radar performance and higher information rates or, second, through doctrinal techniques that permit closer effective separation by altitude stacking on final approach, while maintaining the minimum separation at each altitude. Although the approach glide angle is commonly 3% at most of the European airports, the High Approach Landing System / Dual Threshold Operation procedure (HALS/DTOP), notably experimented by the German Air Traffic Services (DFS) at Frankfurt Airport, can be considered as an indirect application of this latter recommendation.

The second major conclusion emphasises the fact that the spread in speed of the landing aircraft is unfavourable to arrival capacity: the more it increases, the more landing rate decreases. This spread can however be counteracted in several ways: by shortening the length of the common path, or by segregation of aircraft to different runways according to their speed, or by doctrine requiring adherence to specified narrow speed standards.

3.4 Formulation and Representation of Single-runway Capacity

The analytical formulation of airport capacity of 1st and 2nd generations, and its representation, has been extensively reported in the literature and various case studies (cf. Blumstein, 1960; Harris, 1972; Hockaday *et al.*, 1974; Tomic *et al.*, 1976; Newel, 1979; Swedish, 1981; Hamzawi, 1992). These analytical formulations derive capacity from the estimation of the mean inter-operation times, while taking account of

- the uncertainty of the time of movement appearance at various stages of final approach and first climb,
- stochastic variability in speed,
- fluctuation of runway occupancy times, and

- uncertainty in aircraft fleet mix.

The product of all the values for the capacity-influencing factors defines certain **airport states**. For each airport state, the capacity envelope reflects the maximum number of flights that can be accommodated during a given time period depending on the strategy used to mix arrivals and departures (Newell, 1979).

Some characteristics of the capacity envelope shape are illustrated in the literature (cf. Newell, 1979; Ashford *et al.*, 1992; Gilbo 1993; 1997; Horonjeff *et al.*, 1994; Janic 2004), although those shapes are relevant to mixed mode of arrival and departure operations on single-runways, and segregated mode of operations on independent runways only, and do not directly address multiple dependent runways.

In 1979, Newell described how the capacity of a runway configuration depends upon the runway geometry, the instrument flight rules, and the strategy for sequencing various types of aircraft (fleet mix) and operations (traffic mix and related inbound and outbound flows). This research fits with the start of intensive commercialisation and operations of heavy jets. In that scope, the impact of higher proportion of heavy jets on capacity was investigated without, however, analysing the fleet mix paradigm reflecting the related higher number of passengers that those heavy jets can carry out.

In his survey, Newell (1979) attempts to calculate generic capacity values for certain runway configurations, based on the most commonly used input values for fleet mix (light and heavy aircraft), and ATC separations (3 nm on final approach and 2 minutes between departures). Newell shows the reason why arrival capacity is usually more critical than departure capacity due to the limited flexibility left to committed landings.

Newell (1979) analyses the impact of departure and arrival sequencing, and concludes that sequencing yields very little benefit, for both types of operations. Although this statement is relative, it means that there is no real business case for arrival or departure management technologies nowadays, which is rather doubtful.

Although airport operations have changed during the last 25 years and have made airport modelling increasingly complex, Newell's work constitutes without doubt a robust basis for runway modelling. It is however based on the basic principle that the number of events per unit of time is the reciprocal of the arithmetic mean of the time intervals between successive events, without going into further details about the specific formulation of those time intervals

depending upon the type of operations. Due to history, Newell's work needs to be updated regarding several issues, amongst which:

- The introduction of a wider fleet mix, including medium jets and turbo-props;
- The distinction between same and diverging departure tracks, what can make a difference in terms of inter-departure separations due to wake vortex.

Other classical models synthesising the capacity envelope concept use the minimum ATFM separation rules between particular sequences of operations, and the probability of not violating safe separation minima. Those rules are dependent upon runway-use configuration, tactic of sequencing arrivals and departures, fleet mix and weather conditions. The capacity envelope is valid for a given period of time, during which the minimum ATFM separation rules are known and do not fluctuate.

Various tactics to sequence inbound and outbound traffic are investigated (Janic, 2004). At airports composed of independent runways, inbound and outbound traffic might be handled independently and simultaneously, by using a **segregating tactic**. This practice consists in dedicating one or several runways to inbound only, while the rest of runways are dedicated to outbound only.

However, at most airports composed of single or dependent runways, the interdependence between arrivals and departures processes requires tactics to be considered to trade-off between inbound and outbound traffic. The **sequencing tactic** consists in handling an arrival or package of arrivals as soon as possible, followed by a departure or package of departures, or vice versa. This tactic enables us to minimise airborne delay that is more expensive than ground delay, although it thwarts the quality of service: waiting airborne is indeed imperceptible for most of passengers, unlike waiting on stand that makes them dissatisfied. The sequencing tactic can be applied at various levels of traffic packaging. At one extreme, the basic tactic – **alternating tactic** - consists in alternating successively one arrival and one departure (Newell, 1979); at the other extreme, the **hub tactic** is used when arrivals successively follow each other during relatively short periods of time (one hour, half an hour, or a quarter of hour), and then departures follow each other during another successive relative short periods of time. The latter tactic, which consists in accommodating successive banks – also called waves – of arrivals and departures, mostly appeared with hub operations at airports, hence the name (Janic, 2004).

Between those two extremes, several **sequencing tactics** can be used with the aim of optimising capacity management, especially at those airports where holding bays are designed to mitigate the negative impact of backtracking operations due to non-optimum exit location or runway access. At those airports, arrivals and departures are sequenced in order to feed holding bays and use them at their maximum capabilities. Most common is the use of traffic sequencing by the arrival or departure management systems (AMAN/DMAN) with the aim of optimising traffic accommodation and capacity management.

3.5 Strategic versus Tactical Tools

Strategic airport planning requires the ability to examine approximately the implications for the level of service at the airport of a wide range of different scenarios and hypotheses about future conditions.

A number of fast-time simulators (e.g. SIMMOD Plus, TAAM, Airport Machine, and Hermes) provide assistance in the detailed design of airports. In terms of one-shot investment, the prices for one license of such microscopic models vary from a few thousands euros⁵ to more than 40,000 €⁶. Those models also have a steep learning curve, requiring well-trained expert users (Stamatopoulos, 2003). In terms of operational costs, the maintenance and support fees can achieve 25% of the original license price. Such microscopic models are characterised by their great amount of time, effort and expense in terms of data preparation and results analysis. According to an investigation made in 2000 concerning the effort required for an average European airport, setting up a baseline scenario with such macroscopic tools can range between 6 to 9 person-months⁷, while 1.5 person-month is spent for an analytical model. Significant modifications to some of the original assumptions on airport configuration may also take from some person-days to several person-weeks⁸. In addition, these models often suffer from the somewhat paradoxical disadvantage of

⁵ One license of SIMMOD Plus costs 3,000 € in January 2005.

⁶ For one license of TAAM in 2000.

⁷ Valid for SIMMOD and TAAM respectively.

⁸ Valid for TAAM and SIMMOD respectively.

providing too much detail for the needs of strategic airport planning, instead of focusing on the aggregated characteristics of interest (Odoni *et al.*, 1997).

Strategic airport planning is characterised by decision-making with a relatively long-term horizon. It is a fact that the longer term the horizon is, the higher the uncertainty regarding data projections and forecasts. It is therefore legitimate to question and challenge the real value of the detail that can be provided by microscopic simulators. The uncertainty intrinsically linked to modelling results is directly dependent on both the input uncertainty and the degree to which this input affects the output results, i.e. its sensitivity. Providing detailed results with a higher accuracy than their intrinsic uncertainty is totally useless and invaluable. The detailed results provided by such models are not more accurate than aggregated results provided by analytical modelling at a much lower cost. Based on those considerations, it can be concluded that the characteristics of microscopic models increase unnecessarily the cost of decision support, and make sure that they are ineffective as assistance tools to strategic decision-making.

On the opposite side, analytical macroscopic models exist for computing approximate capacities and/or delays associated with each individual airport airside component (i.e. runway system, taxiway and apron/gates), under a wide range of sensitivity analyses, planning alternatives, hypothetical 'what-if' scenarios, and goal seeking options about future conditions at the airport under investigation. These characteristics make analytical models suitable for use by decision-makers at the strategic level of planning. Based on experience at various European airports, the level of detail provided by analytical macroscopic models is sufficiently adequate to assist in decision-making for strategic airport planning, and constitutes the best alternative to optimise cost-effectiveness in airport modelling .

As an example of 2nd-generation macroscopic models, Stamatopoulos (2003) develops MACAD (MANTEA Airfield Capacity And Delays model) under contract with EC. MACAD is a decision support tool suitable to assist airport operators and managers in planning strategically for expanding and optimizing the airfield (strategic airport planning), and for improving operating procedures or managing demand ("slot control and allocation"). This tool is based on the integration of a set of stand-alone macroscopic models. It enables the airport airside system to be examined as a whole, and possible interactions to be identified between the various airside components. It also enables a quick and reliable approximation of capacity and associated delays while minimizing the set of input and related data preparation.

The research hereby primarily focuses on strategic airport planning. Based on the consideration of strategic versus tactical models, the rest of this dissertation will address analytical modelling only.

3.6 The Airport Capacity Allocation Optimisation Problem

Likewise the model for airport capacity assessment, the optimisation of capacity allocation is used by airport traffic managers as an effective assistance to decision-making. The capacity optimisation modelling allows traffic managers to generate effective strategies for managing arrival and departure flows.

The major input that enables solving the capacity allocation problem is the capacity curve describing the interdependence between arrivals and departures under certain operational conditions. The capacity curves, as described here above, provide information about airport operational limits for the complete spectrum of traffic mix, i.e. arrival/departure ratios, for given airport states described by specific sets of weather and related operational conditions.

Given this capacity curve, the problem of airport capacity allocation lies in the ability of selecting the appropriate capacity value from the given arrival/departure ratio ranges to best satisfy the traffic demand (Gilbo, 1993), bearing in mind the possible dynamic variation of this demand. The objective therefore consists in maximizing the use of the available capacity to be allocated to traffic demand subject to allocation criteria, in order to achieve specified objectives like, for instance, minimization of queues, delays and associated costs (Janic, 2004). This problem often calls for optimisation techniques (Gilbo, 1993; Janic, 2004) to best allocate the airport capacity between arrivals and departures and best satisfy the predicted traffic demand over a period of time, under given operational airport conditions. In other words, the optimal solutions of the airport capacity allocation problem are the arrival and departure capacity values for each time period under interest, that minimize the optimisation criteria under consideration.

Gilbo (1993) describes the capacity allocation problem as the evaluation of decision variables – airport capacities – in accordance with predefined optimisation criteria. Two types of criteria can determine the operational effectiveness of traffic accommodation over a given time period of interest: first, the ***total number of flights in the queue***, and second, the ***total delay time*** of the accommodated traffic (i.e. total waiting time in the arrival – holding or stack – and departure queues). It is obvious that these two criteria are strongly

correlated: the larger the queues, the longer the delays. An optimal solution that minimizes the total number of flights in the queue is also expected to provide favourable conditions to minimize delays. The choice of the most appropriate optimisation criterion mainly depends on the type of input data available and the relative complexity of calculating the optimal solutions (Gilbo, 1993). The criteria of total size of the queues will be preferred at the strategic airport planning level, when aggregated data are available or more relevant (e.g. total demand per 15-minute or one-hour time intervals). This criterion – total number of flights in the queue - also entails less complex algorithms to calculate optimal solutions. In contrast, the total delay time is more appropriate for tactical planning purposes, when flight-by-flight data is available.

Gilbo (1993) proposes a mathematical model that considers arrivals and departures as interdependent processes, treats the airport capacities as decision variables, and selects the optimal capacity values from the area delimited by the capacity curves. The underlying algorithm provides the optimal solutions that are the arrival and departure capacity values for each time slot (e.g. 15-minute) that minimize the total arrival and departure queues. The resulting solution to capacity allocation is based exclusively on total demand as input data, and hence, on the total number of flights in the queues. Gilbo (1993) indeed considers that the total demands can be used to calculate the length of the queues, but not the delay time for each individual flight in the queues. Although it is right that flight-by-flight delay time calculation is not possible with aggregated demand data, rough estimates of total delay time can be calculated based on a straightforward formulation.

Based on throughput records, Gilbo's empirical approach to assess practically realisable capacity also enables the dynamic allocation of this capacity over time between arrivals and departures. Gilbo (1993) demonstrated the relevance of linear programming for the optimal allocation of the interdependent airport arrival/departure capacity to the expected traffic demand during a given time horizon. Based on the first optimisation criterion, total number of flights in the queue, Gilbo's strategic optimisation model enables minimizing a weighted sum of arrival and departure queues and delays for all time slots of the time horizon under consideration, at the aggregated level, while taking into consideration a relative cost of slots, and possible traffic mix constraints. This constrained objective can be reduced into a linear programming (LP) problem, which consists in maximising a weighted sum of the cumulative arrival and departure capacities with the same cost of slots and traffic mix constraints.

In 1997, Gilbo extended his research on optimal allocation of airport capacity to the capacity of arrival/departure fixes in the terminal area (Gilbo, 1997). The empirical approach and its extension to the terminal area were then extended through the prioritisation of particular flights of different airlines (Gilbo and Howard, 2000).

Janic (2004) showed that airport capacity allocation is also considerably influenced by the demand distribution over a given time horizon, and the difference between the costs of a unit of the arrival and departure delays, and pattern of changes of the capacity envelope (IFR/VFR conditions, runway-use configuration). The major challenge of airport capacity allocation is the minimisation of induced costs of delays (Janic, 2004), by using the appropriate relationship between traffic demand, the capacity envelope, and the ratio between the perceived departure and arrival cost of delays (Gilbo, 1993; 1997).

According to Janic (2004), the major mission of the ATC Flow Management System is to control the flow of air traffic to match demand, as well as possible, with the available capacity over time and across the various components of the ATC and the airport's network. Many factors cause the increase of air traffic congestion, delays and associated costs. Different strategies and tactics for mitigating congestion and delays have been proposed in the literature during the last decade.

One of the most important functions of air traffic management systems is the assignment of ground-holding times to flights. This commonly used strategy, the **Ground-Holding** (also called gate-holding) **Programme**, came into practice after the 1981 air traffic controllers strike in the United States, and is currently commonly used by the ATC System Command Centre (ATCSCC), in Washington D.C., as well as by the EUROCONTROL Central Flow Management Unit (CFMU), in Brussels. It consists in determining whether, and by how much, the take-off of a particular aircraft headed for a congested part of the ATC system should be postponed to reduce the likelihood of airborne delays. In practice, this strategy consists in holding departures on the ground of origin airports, and determining the optimal take-off times for aircraft flying to congested airports, in order to prevent extensively long arrival delays and associated costs at destination airports (Terrab and Odoni, 1993). Such strategies may require delaying the take-off of some aircraft beyond their scheduled departure time, even when these aircraft are otherwise ready to depart. The motivation for the use of such strategy is the simple fact that, as long as a delay in reaching the destination airport is unavoidable, it is both less costly and safer to absorb this delay on the ground before take-off, rather than in the air. This strategy is highly dependent on prediction of the

demand and capacity profiles over a given time horizon. Terrab (1993) analyses the fundamental case in which flights from many origins must be scheduled for arrivals at a single congested airport, and proposes a deterministic and a stochastic version of the problem. A minimum cost flow algorithm is presented to solve the deterministic problem of ground holding.

Various strategies can be implemented in order to alleviate traffic congestion at airports experiencing high traffic volume, and where traffic volume frequently exceeds operational capacity. Such congested airports are called *spacing* airports by the FAA (Gilbo, 1993) due to their ability to pace the flow of traffic accommodated by the National Airspace System (NAS). In the **ground delay program** (Gilbo, 1993), outbound traffic is dependent on inbound traffic in the way that *controlled delay times* are calculated and assigned to departures in the two to four hours in order to make place to the accommodation of a prescribed arrival acceptance rate. In a similar way, various **airborne delay strategies** can be used in order to 'slow down' the inbound flow in order to prioritise outbound traffic fluidity. The three most commonly used strategies are, by order of usage frequency, **speed control**, **vectoring** and **airborne holding**. The implementation of those strategies usually biases the natural interdependency between arrival and departure operations referred to by Gilbo (1993). From a delay perspective, all those strategies give rise to '*controlled*' flight-level delay with the ultimate objective of minimising system-level delay and, in that way, optimising the user-system equilibrium at airports (Sheffi, 1997). Gilbo (1993; 1997) also proposed another option, which consists in an improved utilisation of the available airport capacity through its efficient and effective allocation to the expected time-dependent demand.

In the scope of tactical allocation of airport capacity, Janic (2004) developed and proposed a heuristic algorithm for the optimisation of airport capacity allocation, the objective function being the minimization of flight/aircraft queues, air traffic delays and associated costs over a given time horizon. This heuristic algorithm uses as input the time-dependent arrival and departure demand, a synthesised capacity envelope, the cost of a unit of flight delay, and a heuristic ("greedy") criterion for the allocation of airport capacity. The major results provided by this algorithm are the minimum time-dependent arrival and departure queues, delays and associated costs, and the interdependent optimally allocated airport arrival and departure capacities. Janic's (2004) "greedy" algorithm aims at reflecting the rule of thumb of ATFM operators to select the interdependent airport arrival and departure capacity from a given capacity envelope and minimize the corresponding queues, delays and associated costs over the given time horizon. To be as close as possible to this rule of thumb, Janic (2004)

used two different criteria, depending whether the average costs of a unit of the arrival and departure delays are equal or different: when those costs are equal, the selection of the maximum sum of the arrival and departure capacity whenever possible on a given capacity envelope is relevant; otherwise, the ratio between the perceived costs of the departure and arrival delays is to be applied. The first criterion is obviously a special case of the second one.

Because it implies making a choice of what looks the best at a given moment, the "greedy" algorithm developed by (Janic, 2004) represents a local optimum, with the hope that such a choice leads to a globally optimal solution. As opposed to dynamic programming in which the outcome of a step depends on the outcome of previous steps, the choice resulting from the "greedy" algorithm ignores any other alternatives, and is totally independent on the outcome of other potential alternatives. It is recognised that this algorithm might not always yield the best solution (Janic, 2004).

Janic (2004) developed a heuristic algorithm to optimise the allocation of runway capacity to the perceived demand according to optimisation criteria close to the common rule of thumb of the ATFM operators in order to minimise queues, delays and associated costs over a given time horizon. In Janic's (2004) approach to allocate airport capacity, the service priority rule for each flight is "first come, first served". The cost of a unit of delay on both arrival and departure flight is determined as an average for the time interval which the capacity envelope is related to.

The "greedy" algorithm was used in a case study at Chicago O'Hare airport (ORD), where both the airport capacity envelopes varied based on IFR and VFR conditions, as well as the average costs of a unit of arrival and departure delay. This case study showed that this algorithm has managed to minimize the queues, delays and associated costs over a given time horizon by appropriate use of the proposed "greedy" criteria, while enabling an appropriate balance of those costs between arrivals and departures (Janic, 2004). Janic (2004) benchmarked the results of the "greedy" algorithm with those obtained by using an integer-programming optimisation model. The "greedy" algorithm provided similar results for this specific case study, while being much closer to reality of ATFM operators as it mimics their common rule of thumb.

Other approaches of the airport capacity allocation problem are proposed. Amongst them, Dell'Olmo and Lulli (2001) use dynamic programming to solve the problem of optimal allocation of airport capacity over a given time horizon. Velazco (1995) proposed an

analytical queuing model to estimate delays while prioritizing arrivals and departures at single runway airport. In this approach, the various strategies to distribute inbound and outbound traffic were equally prioritized during peaks, while arrivals were given non-preemptive priority over departure during off-peaks (Janic, 2004).

An extension of the capacity allocation optimisation problem is the optimisation of runway allocation. One of the major challenges for approach controllers is to determine, based on meteorological conditions and pre-constrained (ATFM-regulated) traffic demand, the runway configuration while maximising the usage of available runway system capacity and minimizing the impact of noise and delay. This decision, that can have serious consequences, is all the more complex since there exists a high combination of operational runway-use configurations and mixed traffic between arrivals and departures. Netjasov (2004) proposed a prototype of expert model to solve this decision-making combinatorial problem based on fuzzy logic. Netjasov's proposed model is based on the fuzzy characteristics of visibility, ceiling, runway condition, wind direction and speed, and planned hourly number of arrivals and departures. While using this methodology, controllers would be assisted in assigning the traffic on runways in use, per aircraft category. Netjasov's expectations are a better utilization of available runway system capacity as well as decrease noise levels and controllers' workload. Those two latter issues are, however, to be demonstrated. Unlike variables affecting capacity that can be qualified only, other variables can be quantified with relative accuracy (for instance, wind direction, wind speed, and planned number of arrivals and departures). The combination of fuzzy modelling - valid for qualitative variables - and pure analytical modelling - powerful for quantitative variables - is therefore expected to increase capacity assessment accuracy according to Netjasov's approach.

3.7 Consultation with the Scientific Community

As reported in the previous Sections of this Chapter, a relatively prolific literature exists regarding runway capacity assessment. However, beyond sensitivity analyses here and there on some particular factors, no literature addresses the specific problem of capacity dynamics and the formulation of capacity fluctuation.

Although this review aims at being as complete as possible, the risk of forgetting some literature remains, as small as it can be. The risk that other researchers address similar issues somewhere else in the world and have not reported the output of their research yet

also exists. In order to minimize this risk, the scientific community was consulted through its major representatives in airport modelling, and this review of literature was complemented by personal communications and discussions with Prof. Andreatta (20 December 2004), Dr. Caves and Dr. Gillingwater (12 and 16 November 2001), Dr. Caves (11 September 2001, 26 October 2005), Dr. Cornelis (27 August 2001 and May 2003), Prof. Donohue (24 November 2004), Prof. Zografos (10 June 2005), Dr. Janic (24 January 2005), Prof. Nastro (4 April 2005), Prof. Toint (14 June 2001), Prof. Walker (13-14 October 2004) and Prof. Odoni (17 December 1999 and 12 July 2006).

The conclusion of this consultation is as follows:

- It is largely accepted that analytical modelling can play a major role as the most appropriate approach for strategic transportation planning in large, and for strategic airport planning in particular. However, and according to Donohue and Zografos, it would be illusory to want to achieve, after much effort, a single recognised analytical model, so it would be difficult to achieve a consensus about this.
- Common urban transportation tools would require major modifications to fit airport needs. Although the general approach of urban transportation can be used for ground circulation efficiency at airports (e.g. use of shortest path algorithms for dynamic taxi routing), the analysis of those techniques reveals that they are not appropriate for runway capacity modelling. From this analysis, it can also be concluded that capacity stability is not a common concept of urban transportation, in terms of elasticity.
- The robustness of capacity assessment is strongly dependent on derivatives of the various factors that affect it. However, the marginal impact of those factors have not been analysed as a whole, deriving into the topic of this research, which is the concept of capacity stability.

To go even further with the consultation of the Scientific Community, a paper was submitted to and accepted by the 6th Air Transport Research Society (ATRS) Conference on 14th June 2002, at Seattle (Desart *et al.*, 2002). This paper raised the importance of capacity accuracy for the purpose of slot allocation, and the impact of its fluctuation on slot scheduling. The following question was clearly raised: *"At an airport where the runway system is the most constraining component, how robust is declared capacity based on a global value, given all the various factors that may affect it due to their fluctuation?"*. In order to answer this

question, the capacity instability concept was introduced and formulated for multiple runway-use configurations. A case study, based on actual airport operations, shows that declaring one total capacity figure, when runways are operated in segregated mode of operations, or when outbound traffic is dependent on inbound flow in hybrid systems, may lead to significant lack of capacity robustness. The case study also shows how the concept of capacity instability enables the quantification of this problem.

This paper was well received by the conference audience and a person even requested to apply this concept at her major airport (LU Communication, 2002). Based on the knowledge of the audience, it was also confirmed that this research had never been addressed.

3.8 Conclusion

The last few decades have witnessed a prolific literary output regarding runway capacity assessment models. Based on the intensive review of this literature, the following conclusions can be drawn:

- In 2nd-generation airport capacity models, the arrival/departure ratio is mostly addressed as a discrete variable, through the five following hypothetical conditions: departure only, mixed mode of operations with pre-emptive priority to departures, balanced arrival/departure, mixed mode of operations with pre-emptive priority to arrivals, and arrivals only. Any intermediate value between those five hypothetical conditions is obtained through extrapolation. Further research should be conducted in order to investigate traffic mix as a continuous variable. To do so, one research option is to extend the current analytical modelling technique to variable and combinatorial sequencing of flight mixing inbound and outbound flows of traffic. Curve fitting will then be used in order to ensure the continuum characteristics of the capacity envelope.
- Although most of the reviewed literature supports their modelling development by relatively robust and validated numerical experiments and case studies, it is to be stressed that most of them focus on a single runway airport. It is believed that there is still some potential to further develop multiple-runway system capacity modelling.

- No model currently exists of the multiple-airport system. Further research could be undertaken in order to extend the models to multi-airport network, in order to complete the airport picture of a wide air traffic management (ATM) network.
- Some variables affecting capacity, like wind direction, wind speed, and planned number of arrivals and departures, can be quantified with relative accuracy. The combination of fuzzy modelling, as proposed by Netjasov (2004), and pure analytical modelling is therefore expected to increase capacity assessment accuracy.

Based on this state-of-the-art of airport capacity modelling literature, it can be clearly concluded that there exists no suitable model which addresses the problem subject to this research. Further consultation and coordination with the Scientific Community, including a paper submitted and presented at the 6th Air Transport Research Society (ATRS) Conference, confirmed that the proposed concept of capacity dynamics and elasticity, and underlying stability, has not been addressed, although it appears to be promising in terms of added value to the airport community, as will be demonstrated in the next Sections of this thesis. That is the reason for which one model will be developed, the subject of the next Chapter.

Chapter 4 - Analytical Formulation of Runway Capacity

4.1 Safety Rules for Runway Operations

To be safe, airport operations need to comply with a minimum and sine qua non set of rules. Those basic rules, enforced through the ICAO standards (ICAO PANS-ATM 1996), are:

1. The runway ahead of any operation in progress (characterised by either a cleared landing or departure) must be free before any other aircraft can be successively cleared to land or line-up for take-off. In no case may traffic controller or pilot violate this **single runway occupancy rule** under instrument meteorological conditions (IMC).

- a. Based on this consideration, a departing aircraft may not be cleared to take-off before the preceding arriving aircraft has safely vacated the runway. Considering two successive movements in time, one arrival a followed by one departure d :

$$t_d^{Take-offClearance} \geq t_a^{RWYexit}$$

- b. From the single runway occupancy rule also follows the time-based regulation between successive departures. If one aircraft departs behind another, it must wait at least until the leading aircraft lifts off (Newell 1979). In other words, for two consecutive departures d_1 and d_2 in time,

$$t_{d2}^{Take-offClearance} \geq t_{d1}^{LiftOff}$$

When the following departure lines-up at the runway threshold, this means that the time interval between the two successive departures d_1 and d_2 must be greater or equal to the departure runway occupancy time of the first departing aircraft, as follows,

$$\tau_{d1,d2} \geq drot_{d1}$$

Under visual meteorological conditions (VMC), the implementation of the single runway occupancy rule can be delegated to pilot's responsibility, but still needs to be enforced for safety reasons.

It is however to be recognised that no risk can be considered as being null in practice; and the risk of unpredictable events like, for instance, runway incursion, burst tyre, incident or even accident, really exists and has to be analysed. Because it might not be possible to terminate an arrival or departure already in progress, a mitigation procedure must be designed to wave off an approaching aircraft if a departure or preceding arrival still occupies the runway. When this risk occurs, missed approach procedure – also called go-around - is performed by the approaching aircraft.

It is also to be mentioned that the single runway occupancy rule might be somewhat relaxed through a special procedure designed by the APATSI Group (ECAC 1997). This procedure, called "Reduced runway separation on the same runway", states that, under specified conditions of visibility (to be determined by local safety case), an aircraft may be cleared to land or depart while a preceding aircraft landing on or departing from the same runway is still on the runway, at more than a specified minimum distance from the threshold. Designed with the aim of maintaining a smooth flow of traffic at critical times by reducing the number of missed approaches, this procedure was proposed to ICAO for review and endorsement at the international level (ICAO 2002). There is no doubt that this procedure will be subject to strict safety cases and will need to be approved by local safety boards and civil aviation authorities before local implementation.

Beyond the consideration of missed approach and special procedures, the single runway occupancy rule remains the basic rule for safe runway operations. In order to make controllers' task easier, and so that missed approaches are minimized, further rules are implemented in support.

2. A second rule states that a departure can be squeezed between two successive landings if, when the preceding arrival vacates the runway, the following arrival is at least a certain **runway lock distance** from the runway threshold.

Assuming that any departure can line-up and take-off within 1 minute or less, there is not much time to spare to free the runway for the next approach and obey the single runway occupancy rule. Should the pilot judge it too risky to land because the preceding departure has not lifted off yet, he can engage a missed approach procedure and go around. This risk for the approach to catch up the take-off is however quite low because, although they both follow the same heading, the distance between the approach and the preceding take-off is usually high, and the departure is in full acceleration process while the approach is expected to decelerate to achieve a runway exit.

3. Unpredictability is intrinsically part of approach procedures: the pilot of a following aircraft on final approach cannot predict when the aircraft ahead of him can vacate the runway, and, by the time he does know, he can no longer adjust his landing procedure. In order to avoid a following aircraft catching up a preceding aircraft on final approach, and to obey the single runway occupancy rule, two aircraft must therefore maintain a safe minimum spacing at all points along the final approach path. When a slower aircraft is following a faster one, the rule mainly applies at the approach gate, i.e. the second aircraft must maintain a distance d_{aa} from the approach gate when the first aircraft reaches the approach gate. This spacing will never be less than the minimum spacing d_{aa} , and will even increase as the aircraft flies along the final approach path. On the other hand, when a fast aircraft is following a slower one, the critical point to be considered in order to ensure the minimum spacing d_{aa} is the runway threshold. At the approach gate, this spacing will be larger than d_{aa} so that **speed differential** is compensated.
4. Beyond the single runway occupancy rule, aircraft must be spaced in such a way that **wake vortices** they generate are dispersed by the time the following aircraft flies to the same point, and that basic rules of aerodynamics required to fly (especially lift) are not violated. Because wake vortex is quickly dispersed for aircraft rolling on the ground, wake vortex rules are not necessary for a departure following an arrival, and vice versa.

For consecutive arrivals the minimum spacing d_{aa} following a heavy jet are increased from 3 to 4 nm if the following aircraft is also a heavy jet, to 5 nm for medium jets and turboprops, and 6 nm for light aircraft.

The rule used by Newell (1979) is as follows: the wake vortex rules imply a minimum time separation of about 1 minute for consecutive departures; however, if the leading aircraft is a heavy jet, this time separation is increased to 1'30" if the following aircraft is also a heavy jet and to 2 minutes otherwise. Due to the introduction of a wider fleet mix, Newell's study (1979) is however to be updated while taking into account medium jets and turboprops, and the split of outbound traffic on same or diverging departure tracks.

According to ICAO (1996)⁹, a take-off may not be cleared prior to the leading aircraft starting on its first turn when the following departing aircraft is heading to another departure fix (diverging track). This separation is usually 1 minute and enables the preceding aircraft to evacuate the runway and turn. When the following departing aircraft is heading for the same departure fix as its predecessor (same track), the following departure has to be distanced by the minimum wake vortex separation (minimum 3 NM).

4.2 Calculating Throughput and Capacity

4.2.1 Rate, Flow and the Peak-Sustainability Paradox

As shown in Chapter 3, most of the research literature on runway capacity modelling deals with the "number of operations", i.e. the sum of both arrivals and departures. There are however many other indicators which one could count: number of arrivals or, separately, departures, number of aircraft distributed according to a given and possibly customised classification (e.g. light, small, medium, heavy), per market segment (e.g. domestic, "Shenghen", "non-Shenghen", international,), number of passengers, inbound or outbound

⁹ It is to be noted that: arrival separations are distance-based and have therefore to be converted into time-based separations, that requires both wake vortex separation (or final approach path length) and average speed on final approach. Departure separation is time-based and there is therefore no need for either speed on 1st climb, that is aircraft performance dependent, or distance to first turn.

payload processed by a cargo terminal, etc. Disregarding what those indicators might represent, a global concept of counting events and calculating related rates and flows is required in order to put capacity into the right context.

A prerequisite to count events is the specification of a reference system. For instance, to count the number of movements (arrival and departure) in particular, one needs to choose any point along the common path to arrivals and departures. It makes no difference which point is chosen, provided that this point is common to all the indicators under consideration. For reasons of expediency, this point must be a landmark, such that an event can be measured at that point. Since departures are most commonly released at a point near the threshold for arrivals, runway threshold is commonly recognised as the reference system at which the number of movements is counted. However, this reference system might be changed (e.g. runway entry point for intersection take-off) providing that data collection at that new reference marker is made possible, easy and accurate.

Let us consider some time reference t_0 from which any event is counted. Let $T = (t_n - t_0)$, a time period between the very first event (reference point t_0) and the n^{th} event.

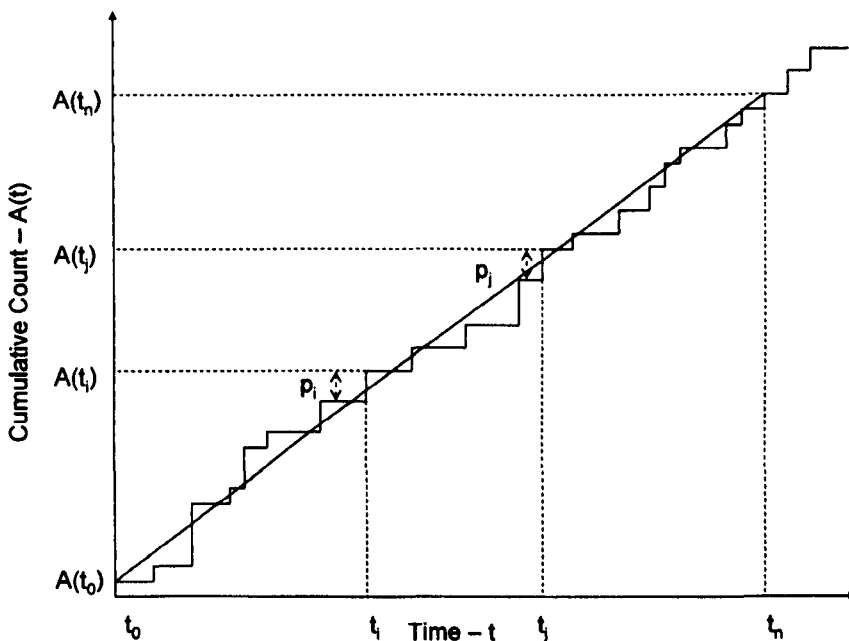


Figure 4-1– Cumulative count and definition of average flow

As shown in Figure 4-1, the **average rate of events** between two times t_0 and t_n is defined by the slope of the cumulative count function $A(t)$, and is represented by

$$\lambda(t_0, t_n) = \frac{(A(t_n) - A(t_0))}{(t_n - t_0)} = \frac{n}{T}$$

Equation 4-1

Let τ_j , the time interval between two successive events or counts ($j-1$) and j occurring at time t_{j-1} and t_j .

$$\tau_j = t_j - t_{j-1}$$

Equation 4-2

The time period $T = (t_n - t_0)$ can also be expressed as $T = \sum_{j=1}^n \tau_j$. Consequently, the number of events per unit of time calculated over the time period T is

$$\lambda(t_0, t_n) = \frac{n}{\sum_{j=1}^n \tau_j} = \frac{1}{\frac{1}{n} \sum_{j=1}^n \tau_j} = \frac{1}{\bar{\tau}}$$

Equation 4-3

In other words, **the number of events per unit of time is the reciprocal of the arithmetic mean of the time intervals between successive events**. Equation 4-3 leads to the basis for any further research of flow and capacity modelling.

The cumulative function $A(t)$ is a step function, and each step is unitary when the performance indicator under investigation is an event. So it is when one counts the number of aircraft (arrivals, departures, movements, inbound heavies, etc) because only one aircraft can land or take-off at any time. However, when the step is not unitary and is characterised by its height P_j at the j^{th} step, the **average flow** is determined by the slope of the cumulative function, multiplied by the average step height over the time period. For

instance, when the objective is to count travelling passengers instead of aircraft, the cumulative function $A(t)$ has a step of height P_j at the j^{th} crossing time if $P(t_j) = P_j$ is the total number of passengers on board the j^{th} aircraft. The average flow of passengers is therefore

$$\lambda(t_0, t_n) = \frac{\sum_{j=1}^n P_j}{\sum_{j=1}^n (t_j - t_{j-1})} = \frac{\bar{P}}{\tau}$$

Equation 4-4

Therefore, the flow of passengers is determined by the quotient of the average number of passengers per aircraft and the average time interval between successive aircraft.

For ease of mathematical analysis, one could be tempted to derive, from Equation 4-4, the flow

$$\lambda(t) = \frac{\delta A(t)}{\delta t}$$

Equation 4-5

It is however to be noted that counts are integer values and the cumulative function is therefore discrete and not continuous. Because the cumulative function is a step function, the instantaneous flow $\lambda(t_0, t_n)$ has a limit of either 0 or ∞ over a relatively small period of time, i.e. when the time period tends towards 0 ($T = (t_n - t_0) \rightarrow 0$). On the other hand, the average $\lambda(t_0, t_n)$ might not be of much interest for a relatively large period of time $T = (t_n - t_0)$, since it removes the surges which one may wish to describe and analyse. Choosing the appropriate length of time period is therefore paramount when one focuses on sustainability on one hand, or on the surges of the performance indicator under investigation on the other. This is what might be called the **peak-sustainability paradox**. According to Newell (1979), this choice should be made in such a way that the $A(t)$ curve stays fairly close to a straight line over some time period which includes many events.

The time period is most commonly 1 hour in transportation modelling, and flows are expressed in unit of number per hour. It can however vary in the two following ways:

- The time period is very often reduced to 30, or even 15 minutes, by modellers who aim at reflecting and analysing peaks;
- It can also be extended to several hours (usually 3) by those who aim at analysing sustainable periods.

The peak-sustainability paradox is illustrated in Chapter 5 - Runway System Capacity Analysis: A Case Study.

4.2.2 Basic Concepts of Throughput and Capacity

While referring to Equation 4-3, the number of events per unit of time calculated over a given time period $T = \sum_{j=1}^n \tau_j$ is the inverse of the average time interval between successive events.

$$\lambda(t) = \frac{1}{\tau}$$

Equation 4-6

When the events are measures of accommodated demand, the result of Equation 4-6 is a **flow** - also called **throughput** - as described in Section 4.2.1. However, when the time intervals τ_j are driven by the flight rules and chosen to have their minimum allowed values, then Equation 4-6 defines capacity.

Capacity must be uniquely specified by a variety of subsidiary conditions like, for instance, the single runway occupancy rule or the separation minima imposed by wake vortex constraint. Those flight rules impose restrictions on the times at which individual counts can occur, disregarding what is counted (arrival, departure, number of passengers, number of heavy, movements, etc). More specifically, those rules determine the time interval τ_j between two successive events or counts $(j-1)$ and j .

Although slight but nevertheless paramount, the distinction between throughput and capacity is most commonly omitted by unscrupulous modellers. For instance, fast-time simulators are widely used for capacity analysis. Aiming at generating direct capacity figures while mimicking airport operations and "replaying" airport accommodated traffic is however unrealistic, because flow includes a random dimension in terms of spacing. Fast-time

simulators do indeed generate throughput, as well as delay figures for various demand/throughput ratio values (TAAM, 2001; SIMMOD, 2003), but they do not directly generate capacity figures. Various capacity figures can, however, be derived from the dependency between delay and demand/throughput ratio for predefined acceptable levels of delay. In order to clearly distinguish throughput and capacity in the rest of this research, **throughput** will be represented by ϕ whilst **capacity** will be labelled by γ .

As far as airport operations are concerned, it is to be noted that the restrictions on a particular counting time t_j mainly depends upon certain properties of the j^{th} event, but also upon the type and properties of the preceding counted event ($j-1$). However, it does not generally depend upon events further back.

One approach used for capacity assessment is to substitute aggregated occurrences of events for the cumulative sum of events used in throughput analysis. In this approach, the operations are aggregated to reflect identical circumstances or properties, for instance arriving heavy aircraft followed by departing light aircraft. If α represents the properties of the $(j-1)^{\text{th}}$ event, and β the properties of the j^{th} event, then one obtains the same time interval τ_j whenever one collects such terms during fully saturated periods, and

$$\tau_j = \tau_{\alpha\beta}$$

Equation 4-7

Beyond the peak-sustainability paradox, choosing the appropriate level of event aggregation is another paramount concern for modellers. For instance, one could cluster the events by aircraft type, with similar aircraft performance (maximum landing weight, maximum take-off weight), or decompose it further into pilot behaviours, to reflect potential 'save-brakes' policy. As reported in Chapter 2, airport operations can also be clustered based on the airborne separation required by wake vortex separation. That way, aircraft types are clustered into light, medium and heavy jets based on their maximum take-off weight (ICAO 1996). In general, one could decompose the classification as fine as necessary so that all the time intervals $\tau_{\alpha\beta}$ are equal for each pair (α, β) of each aircraft class, or can be identified as a statistical distribution. In this latter case, one deals with arithmetic averages of the time intervals $\tau_{\alpha\beta}$ and their standard deviation. The choice of the right level of aggregation

definitely depends on the marginal added value of any further sub-clustering in terms of output quality.

The probability that a certain number $n_{\alpha\beta}$ of events characterised by the properties α of the preceding aircraft and the properties β of the following aircraft occur amongst a total number n of successive events is defined by

$$p_{\alpha\beta} = n_{\alpha\beta} / n$$

Equation 4-8

By grouping Equation 4-7 and Equation 4-8 into Equation 4-6, the capacity can be expressed as

$$\gamma = \frac{1}{\sum_{\alpha,\beta} p_{\alpha\beta} \tau_{\alpha\beta}}$$

Equation 4-9

Let $[P]$ the probability matrix composed of the elements $p_{\alpha\beta}$, and $[\Psi]$ the separation matrix composed of the inter-event separation $\tau_{\alpha\beta}$, the matrix representation of Equation 4-9 is therefore

$$\gamma = \frac{1}{[P] \times [\Psi]}$$

Equation 4-10

Equation 4-9 is valid when the performance indicator is related to unitary events, aircraft to be specific (arrivals, departures, or number of air traffic movement), as only one aircraft can cross the reference marker at any one time. When one wishes to count the number of passengers instead of aircraft, it is necessary to take account of the arithmetic average occupancy of each aircraft type. The calculation of this average requires knowing the total number of passenger on board, what is usually considered as commercially sensitive by the airlines. In order to alleviate this, an alternative is to consider the average seating capability

\overline{S}_β for all the aircraft type β (easy to be collected from aircraft information repository), and to multiply it by the average load factor l_β for that same type of aircraft. This latter information can be provided either by airport operators or airlines as aggregated data in such a way that it is less commercially sensitive than total number of passengers on board. In such a case, the passenger capacity is determined by

$$\gamma_p = \frac{\sum_{\beta} p_{\beta} l_{\beta} \overline{S}_{\beta}}{\sum_{\alpha, \beta} p_{\alpha\beta} \tau_{\alpha\beta}}$$

Equation 4-11

Unconstrained passenger capacity is obtained for maximum load factor of 100%.

4.3 Synthesising Runway Capacity

Deriving the new concepts of capacity dynamics and stability on the basis of innovative – and not proved - capacity approaches would be similar to constructions on quicksand. Synthesizing these new concepts therefore requires a strong basis to be established. This basis must be recognised by the Scientific Community and had to be proved through appropriate applications in the airport operational environment. It is found necessary to explicitly describe the methodology for runway capacity assessment in this Section, as it will be used as a foundation in the next Chapters of this thesis. This methodology is mainly based on models developed by Blumstein (1959) and Newell (1979).

4.3.1 Arrivals Only

The basic concept of capacity described in Section 4.2.2 formulates capacity as the inverse of the time interval between successive approaches. Let τ_{aa} this time interval, then the basic formulation of arrival capacity γ_a is :

$$\gamma_a = \frac{1}{\tau_{aa}}$$

Equation 4-12

However, a runway is rarely used for one single aircraft type. Most often, inbound traffic is relatively heterogeneous, and is constituted by several different types of aircraft. Each type of aircraft has its own constraints in terms of aerodynamics and ground performance and, consequently, in terms of wake vortex separation minima and runway occupancy time. The time interval between successive approaches must therefore take into consideration both the probability $p_{\alpha\beta}$ that an aircraft of type α is followed by an aircraft of type β and the minimum inter-arrival time $\tau_{\alpha\beta}$ required between these two types of aircraft in such a way that the following approach is not put in danger by the turbulence generated by the trailing aircraft, and in order to ensure safe operations.

The in-trail separation minimum part of Equation 4-12 is therefore a weighted average of the various inter-arrival times $\tau_{\alpha\beta}$, defined as follows:

$$\tau_{aa} = \sum_{\alpha,\beta} p_{\alpha\beta} \tau_{\alpha\beta}$$

Equation 4-13

and, consequently, the capacity for arrivals γ_a is defined by

$$\gamma_a = \frac{1}{\sum_{\alpha,\beta} p_{\alpha\beta} \tau_{\alpha\beta}}$$

Equation 4-14

In the previous equations, inter-arrival spacing is expressed in time. However, those separations are most often expressed in distance (NM). Some conversion is therefore required.

Under IFR conditions, the airborne separation between two successive approaches α and β is driven by the radar provision δ^{Radar} and the wake vortex constraints $\delta_{\alpha\beta}^{WakeVortex}$, whichever of those two factors is the greatest. Unlike wake vortex separation, radar provision is driven by technology only, and independent of aircraft type. Thus, the separation minima $\delta_{\alpha\beta}$ between two consecutive approaches α and β is determined by

$$\delta_{\alpha\beta} = \max(\delta_{\alpha\beta}^{WakeVortex}, \delta^{Radar})$$

Equation 4-15

The airborne separation minimum between successive arrivals on final approach has to be ensured over the common approach path. In order to convert distance-based separation minima into time-based separation, two situations are to be considered:

1. When the trailing aircraft has a speed greater than or equal to the leading aircraft speed, the closer the two aircraft fly to the runway threshold on the common approach path, the smaller the spacing between the aircraft. This first situation is known as the ***closing case***. This case is also called the overtaking case in some literature; however, this latter is not recommended because it is misleading as aircraft cannot overtake each other on final approach.
2. When the speed of the leading aircraft exceeds that of the trailing aircraft, the more they fly along the common final approach path, the more they separate from each other. The second situation is referred to as the ***opening case***.

Thus, depending upon approach speed differential between two consecutive approaches, in-trail spacing can vary along the common approach path. In order to be enforced, in-trail separation minima are to be measured either at the runway threshold (closing case) or at the entry gate (opening case), i.e. the start of the common final approach path. Both situations are illustrated and discussed later in Figure 4-2, Figure 4-3 and Figure 4-4.

Let two consecutive approaches α and β ; the following notations are used in the formulation of the inter-arrival separation:

ρ , the length of the common approach path, usually between the outer marker and the runway threshold;

v_x , the average approach speed of an aircraft of class χ along the common approach path;

$arot_x$, the average arrival runway occupancy time of an aircraft of class χ .

Based on these notations, we can now define the airborne separation minima for each of the closing and opening cases.

1. The closing case ($v_\alpha \leq v_\beta$)

In the closing case (Figure 4-2), the spacing between the two consecutive approaches decreases as they approach the runway threshold. In order to be enforced all along the approach path, the separation minimum $\delta_{\alpha\beta}$ has to be measured at runway threshold.

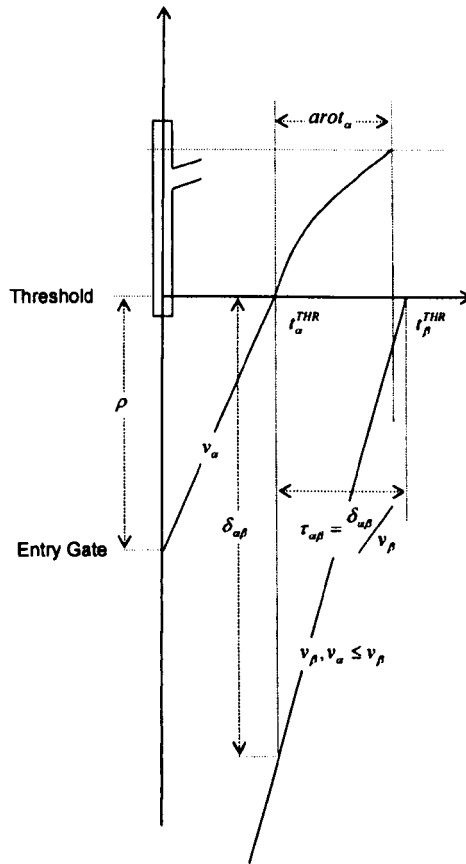


Figure 4-2 - Space-time diagram for in-trail separation minima for the closing case

Beyond the distance-based separation minima $\delta_{\alpha\beta}$, the time-based separation at runway threshold between a leading approach α and a following landing aircraft β depends upon the speed of the trailing aircraft v_β , and can be expressed as follows :

$$\tau_{\alpha\beta} = t_\beta^{THR} - t_\alpha^{THR} = \frac{\delta_{\alpha\beta}}{v_\beta}$$

Equation 4-16

2. The opening case ($v_\alpha \geq v_\beta$)

In the opening case, the distance-based spacing between the two consecutive approaches increases as they approach the runway threshold. In order to be enforced all along the approach path, the separation minimum $\delta_{\alpha\beta}$ has therefore to be measured at the entry gate, and not at the runway threshold. Two different tactics can be considered in order to enforce the appropriate separation at the entry gate, depending whether the separation minima are to be applied downstream or upstream of this entry gate. In the first case (downstream entry gate tactic), the following aircraft is virtually maintained at the entry gate (more practically on holding) until the leading aircraft flies the required safe distance downstream the entry gate (as illustrated in Figure 4-3). In the second case (upstream entry gate tactic), the separation is enforced upstream the entry gate for the two aircraft (Figure 4-4), i.e. both aircraft are separated as soon as the leading aircraft flies over the entry gate.

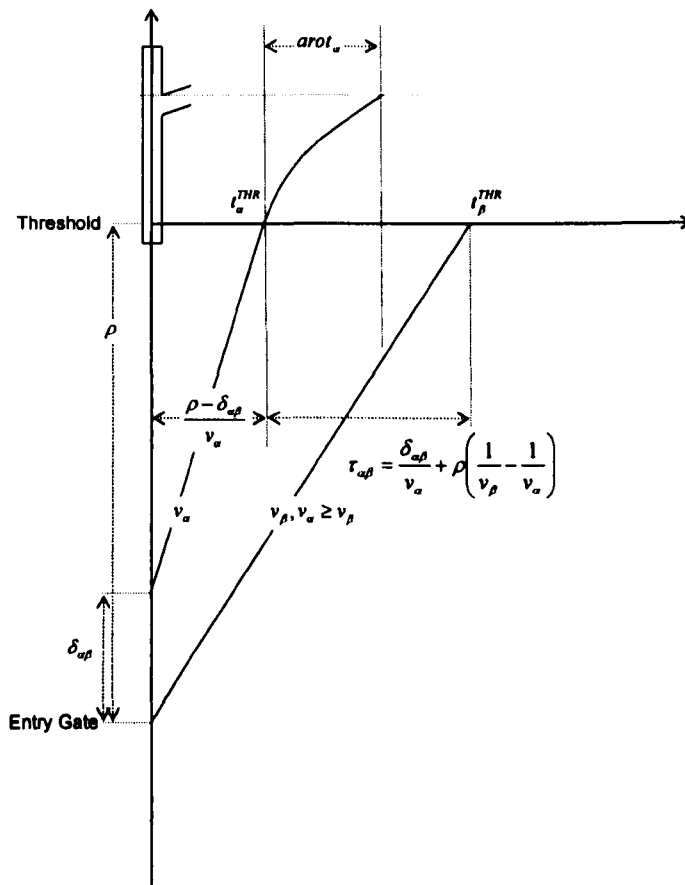


Figure 4-3 - Space-time diagram for inter-arrival spacing, opening case, downstream entry gate tactic

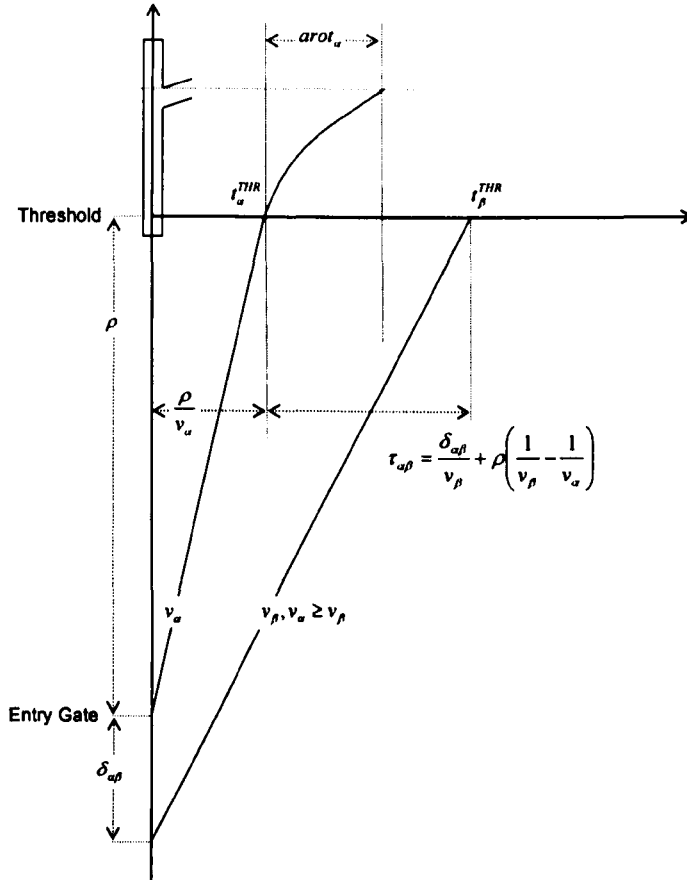


Figure 4-4 - Space-time diagram for inter-arrival spacing, opening case, upstream entry gate tactic

Although separation must be enforced at the entry gate in the opening case, one must not forget that the reference point for counting events is the runway threshold, as specified in Section 4.2.2 on the “Basic Concepts of Throughput and Capacity”. When the following aircraft is allowed to be outrun by the leading aircraft to ensure separation minima (“downstream entry gate” tactic), the minimum time-based separation is defined by the difference of the time of the following aircraft at the threshold

$$t_{\beta}^{THR} = \frac{\rho}{v_{\beta}}$$

and the time of the preceding at that same threshold

$$t_{\alpha}^{THR} = \frac{\rho - \delta_{\alpha\beta}}{v_{\alpha}}$$

The time-based separation minima between the leading approach and the following one is therefore

$$\tau_{\alpha\beta} = t_{\beta}^{THR} - t_{\alpha}^{THR} = \frac{\rho}{v_{\beta}} - \frac{(\rho - \delta_{\alpha\beta})}{v_{\alpha}},$$

which gives, after reduction,

$$\tau_{\alpha\beta} = \frac{\delta_{\alpha\beta}}{v_{\alpha}} + \rho \left(\frac{1}{v_{\beta}} - \frac{1}{v_{\alpha}} \right)$$

Equation 4-17

On the other hand, when the separation is ensured as soon as the leading aircraft passes the entry gate ("upstream entry gate" tactic), the time-based separation minima between the leading approach and the following one is therefore

$$\tau_{\alpha\beta} = t_{\beta}^{THR} - t_{\alpha}^{THR} = \frac{(\rho + \delta_{\alpha\beta})}{v_{\beta}} - \frac{\rho}{v_{\alpha}},$$

which gives, after reduction,

$$\tau_{\alpha\beta} = \frac{\delta_{\alpha\beta}}{v_{\beta}} + \rho \left(\frac{1}{v_{\beta}} - \frac{1}{v_{\alpha}} \right)$$

Equation 4-18

In this research, these two possible tactics are considered for the purpose of modelling rigour, completeness and understanding. It is also to be recognised that, from a safety perspective, ATC is likely to favour the upstream tactic, what confirms in some way ATS

conservatism. However, it is to be recognised that the decision concerning the choice of one tactic rather than the other has an impact on capacity, the significance of which remains to be demonstrated from an operational point of view. This is probably the reason for which most of the airport capacity models reviewed in Chapter 3 either deliberately ignore this issue or, at least, leave it unresolved.

As reported in Section 4.1, the single runway occupancy rule imposes that a preceding aircraft α has to vacate the runway by the time the following committed landing β passes over the threshold. In other words, the runway occupancy time $arot_{\alpha}$ of the preceding aircraft α must be less than the airborne separation minima between the two consecutive landings. When this condition is not met, the following approach has to initiate a missed approach. While taking this additional constraint into account in Equation 4-16, Equation 4-17, and Equation 4-18, the time-based separation minima between two consecutive approaches α and β is therefore

$$\tau_{\alpha\beta} = \begin{cases} \max\left(arot_{\alpha}, \frac{\delta_{\alpha\beta}}{v_{\beta}}\right), & \text{if closing case} \\ \max\left(arot_{\alpha}, \frac{\delta_{\alpha\beta}}{v_{\alpha}} + \rho\left(\frac{1}{v_{\beta}} - \frac{1}{v_{\alpha}}\right)\right), & \text{if opening case, with the "downstream entry gate" tactic} \\ \max\left(arot_{\alpha}, \frac{\delta_{\alpha\beta}}{v_{\beta}} + \rho\left(\frac{1}{v_{\beta}} - \frac{1}{v_{\alpha}}\right)\right), & \text{if opening case, with the "upstream entry gate" tactic} \end{cases}$$

Equation 4-19

Although the single runway occupancy rule has to be enforced at any time, it has to be recognised that, in practice, the airborne separation is greater than the runway occupancy time most of the time, especially when back-tracking on the runway is not common practice, and for those airports where radar provision does not permit separation less than 3 nm. Although Equation 4-19 is required to be complete from a modelling point of view, the single runway occupancy rule is usually not as critical as the compliance with airborne separation minima for consecutive arrivals operations.

4.3.2 Departures Only

In a similar way as arrival capacity, let us analyse what determines departure capacity. While referring to Equation 4-9, the capacity for departures γ_d is defined by

$$\gamma_d = \frac{1}{\sum_{\alpha, \beta} p_{\alpha\beta} \tau_{\alpha\beta}}$$

Equation 4-20

This capacity is based, on one side, on the probability that two successive departures of classes α and β follow each other and, on the other, on the minimum inter-departure time between those two successive aircraft in order to ensure safe operations. Under IFR, the time interval between successive departures is governed by both the single runway occupancy rule and the airborne separation minima due to wake vortex constraints.

As reported in Section 4.1, the single runway occupancy rule imposes that a departing aircraft β may not enter the runway, i.e. be cleared to line-up, before the preceding departing aircraft α lifts off.

$$t_{\beta}^{LineUpClearance} \geq t_{\alpha}^{LiftOff}$$

Assuming that the runway is committed for a given departure as soon as the departure is cleared to line-up, up to this departure lifts off, this means that the time interval $\tau_{\alpha\beta}$ between two successive departures α and β on a same runway must be greater or equal to the departure runway occupancy time of the leading departing aircraft α , i.e.

$$\tau_{\alpha\beta} \geq drot_{\alpha}$$

In order to avoid any incident due to wake vortex, the time interval $\tau_{\alpha\beta}$ between two successive departures α and β must also be greater or equal to the airborne separation minima, i.e.

$$\tau_{\alpha\beta} \geq air_{\alpha\beta}$$

The airborne separation minima rule depends upon the speed differential of the successive departures and whether they fly the same departure fix (same departure track) or follow diverging tracks.

According to ICAO (1996)¹⁰, a take-off may not be cleared prior the leading aircraft started on its first turn when the following departing aircraft is heading another departure fix (diverging track). This separation is usually 1 minute and enables the preceding aircraft to evacuate the runway and turn. When the following departing aircraft is heading the same departure fix as its predecessor (same track), the two departures have to be distanced by the minimum wake vortex separation (minimum 3 NM).

If the objective is to calculate capacity, the time between successive events is kept to its minimum value. Because both departure runway occupancy time and airborne separation are measured from a common reference marker (i.e. usually the runway threshold), the time interval $\tau_{\alpha\beta}$ between any departure α followed by a departure β is governed by the larger value between the departure runway occupancy time of the leading aircraft $drot_{\alpha}$ and the airborne separation $air_{\alpha\beta}$ between the two successive departures, i.e.

$$\tau_{\alpha\beta} = \max(drot_{\alpha}, air_{\alpha\beta})$$

Equation 4-21

¹⁰ It is to be noted that: arrival separations are distance-based and have therefore to be converted into time-based separations, which requires both wake vortex separation (or final approach path length) and average speed on final approach. Departure separation is time-based and there is therefore no need for either speed on 1st climb or distance to first turn, which is aircraft performance dependent.

Equation 4-21 defines the minimum separation that should be applied to ensure safe sequences of successive departures. The departure capacity γ_d can be synthesised as follows:

$$\gamma_d = \frac{1}{\sum_{\alpha, \beta} p_{\alpha\beta} \max(drot_{\alpha}, air_{\alpha\beta})}$$

Equation 4-22

4.3.3 Mixed Mode of Operations

Any sequence of inbound (arrivals, landings) and outbound (departures, take-off's) can be decomposed into runs of consecutive landings, consecutive take-off's, and alternating sequences of landings and take-off's. Such operation is commonly referred to as mixed mode of operations, and is the only mode of operations at single-runway airports. We have already considered the rates for consecutive arrivals (Section 4.3.1) and consecutive departures (Section 4.3.2); the main concern is now with the rates for alternating arrival and departure sequences.

In terms of modelling, there are three commonly recognised ways of mixing arrivals and departures. The more common way of mixing operations however resides in the first tactic, called alternating arrival and departure singletons, which consists in increasing spacing between successive approaches in order to insert a departure. The second tactic, called pre-emptive priority to arrivals, consists in inserting one or several departures between successive arrivals while maintaining the separation minima between those successive approaches. In a similar way, the third tactic, named pre-emptive priority to departures, consists in inserting arrival(s) between successive departures without increasing the separation minima between those departures. Although the first tactic might result in some departure capacity without decreasing arrival capacity, the second tactic is seldom used from an operational perspective due to low inter-departure spacing minima compared to in-trail separation minima.

In order to formulate capacity for each of these tactics, the concept of aggregation referred to in the basic formulation of capacity (Section 4.2.2) needs to be extended. So far, the concept of aggregation is applied to aircraft type only in Section 4.3.1 and Section 4.3.2. In mixed mode of operations, the properties of the classes α and β of successive operations

must reflect both the possible various aircraft type, and the type of operation (landing or take-off). Thus, a movement needs to be characterised according to its type of aircraft - whether it is light, medium or heavy - and whether it is an arrival or departure. Let us call **modelling cluster** each class resulting from the aggregation process, involving more than one classification criteria.

4.3.3.1 Alternating Arrival and Departure Singletons

Let us first consider alternating sequences of arrival and departure singletons, therefore resulting in equal numbers of each type of operation. Figure 4-5 illustrates an example of such an alternating sequence, in which a departure d is squeezed between two successive approaches a_1 and a_2 , i.e. a sequence a_1da_2 . To better determine the capacity of such sequences, let the sequence a_1da_2 be split in a first sub-sequence arrival-departure a_1d and a second one departure-arrival da_2 .

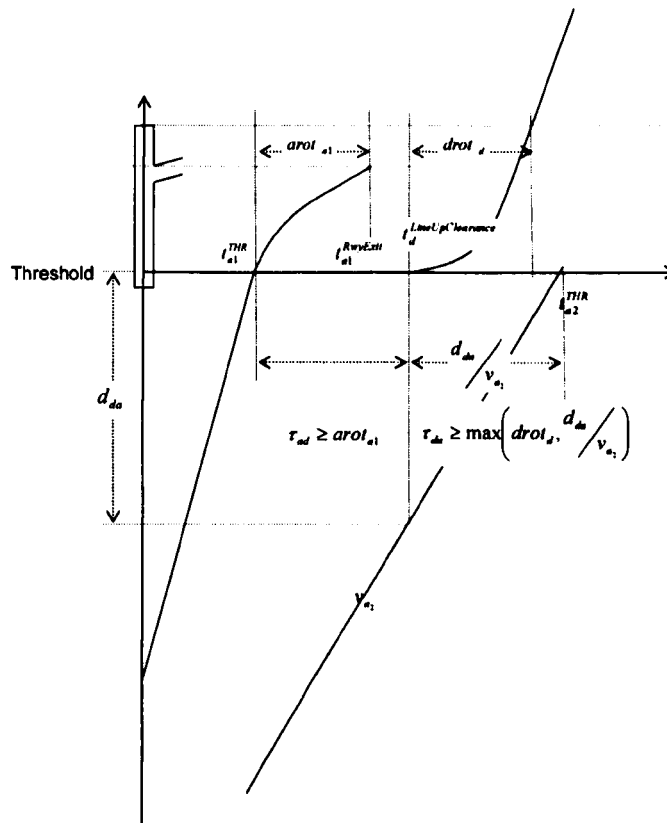


Figure 4-5 – Alternating Arrival and Departure Singletons

When considering the first sub-sequence a_1d from the point of view of the single runway occupancy rule, a departing aircraft d may not be cleared to take-off before the preceding arriving aircraft a_1 has vacated the runway. In other words, and while referring to Figure 4-5,

$$t_d^{LineUpClearance} \geq t_{a1}^{RwyExit}$$

The time reference of any sequence is the time measured over the runway threshold. When the departure crosses the active holding stop bar in order to line up, this means that the time interval τ_{ad} between an arrival and the successive departure must be greater or equal to the arrival runway occupancy time $arot_{a1}$ of the first landing aircraft a_1 , which may depend somewhat on the type of this aircraft and the runway layout:

$$\tau_{ad} \geq arot_{a1}$$

Equation 4-23

Let us now consider the second sub-sequence da_2 . Below a certain distance of the runway threshold, it is certainly neither efficient nor safe to delay an arrival that has been committed to land. For safety reasons, and in order to avoid high rates of missed approach, a second rule states that a departure can be squeezed between two successive landings if the following arrival is further than a certain **runway lock distance** d_{da} from the threshold when the departure is cleared to line up. If the arriving aircraft is at less than the distance d_{da} from the threshold, the departure may not be cleared to line-up. Depending on local operational practices, this distance can range between 2 to 8 NM.

$$\tau_{da} \geq d_{da} / v_{a2}$$

The previous rule is based on the assumption that the departure is able to take-off and evacuate the runway within the time required by the next approach to cover the runway lock distance, which depends upon the speed of the arrival. If this additional condition is not met, then the single runway occupancy rule is violated and, consequently, either the departure may not be cleared to occupy the runway, or the next approach must be aborted. In order to minimize the rate of missed approaches to the single fact of flight profile uncertainty, a departure will be cleared to take off providing that the runway is free before the next arrival passes over the threshold. The minimum time between a departure and the next arrival can thus be formulated as follows:

$$\tau_{da} \geq \max \left(drot_d, \frac{d_{da}}{v_{a2}} \right)$$

Equation 4-24

It is however to be mentioned that conditional take-off clearance allows a departing aircraft to line-up as soon as the preceding arriving aircraft has passed the height of active holding stop bar. This enables the departure runway occupancy time to be reduced by saving the line-up time, and thus this increases the chance to squeeze a departure within the condition formulated in Equation 4-24.

The total time interval τ_{ada} required by the sequence a_1da_2 is defined by the sum of the time intervals τ_{ad} and τ_{da} for the two sub-sequences a_1d and da_2 .

According to the two constraints Equation 4-23 and Equation 4-24, the maximum rate of alternating arrival and departure operation can be achieved only when the arrivals are spaced with a time headway τ_{ada} equal to the runway occupancy time of a landing plus the time required to cover the runway lock distance, as mentioned by Newell (1979), but constrained by departure runway occupancy time:

$$\tau_{ada} \geq arot_{a_1} + \max\left(drot_d, \frac{d_{da}}{v_{a_2}}\right)$$

Equation 4-25

The sequence a_1da_2 can be composed of any type of arriving and departing aircraft. In addition, whilst counting the events from the agreed reference system, which is commonly the runway threshold, any sequence a_1da_2 counts for two movements: one arrival and one departure. Therefore, the capacity γ_{ad} for alternating operation is

$$\gamma_{ad} = \frac{2}{\sum_{\alpha} p_{\alpha} arot_{\alpha} + \sum_{\alpha, \beta} p_{\alpha\beta} \max\left(drot_{\alpha}, \frac{d_{ad}}{v_{\beta}}\right)}$$

Equation 4-26

In practice, it is relatively difficult for ATC to consider all these parameters, especially because they are subject to unpredicted fluctuations. To make life easier for controllers, some local Air Traffic Services (ATS) operating this type of mixed mode of operations define an arrival-departure-arrival distance d_{ada} , which is the minimum distance between two successive approaches that enables us to insert a departure without jeopardizing the successful landing of this second approach.

As illustrated in Figure 4-6, and in order to minimise missed approach and leave it to flight profile uncertainty, the arrival-departure-arrival distance d_{ada} must be chosen by ATS in such a way that

$$\tau_{ada} \geq \max(arot_{a1}) + \max\left(\max(drot_d), \frac{d_{da}}{\min(v_{a2})}\right)$$

Equation 4-27

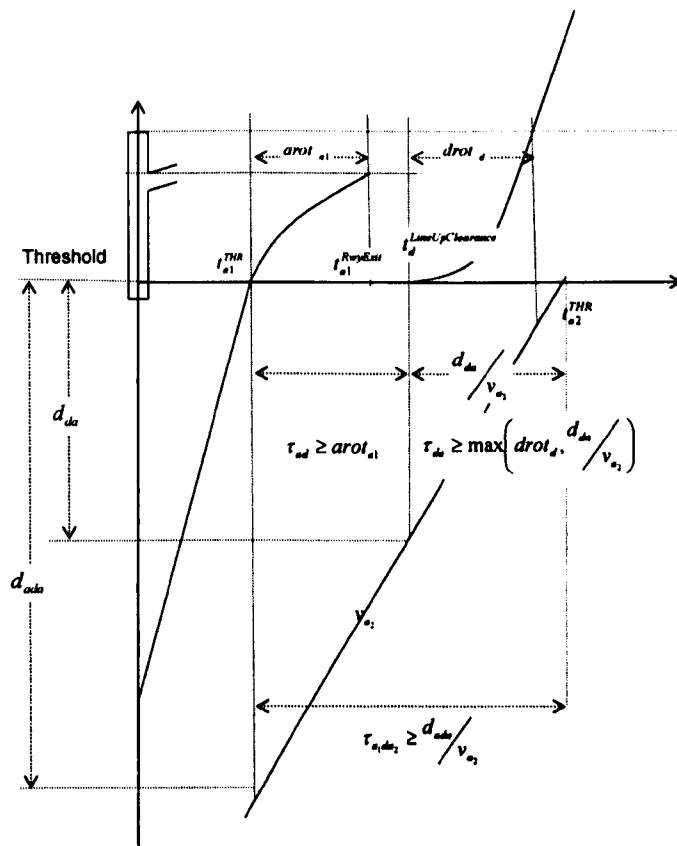


Figure 4-6 – Simplified Procedure for Alternating Arrival and Departure Singletons

Based on this “operational” simplification, Equation 4-26 on the capacity γ_{ad} for alternating operation can be simplified into

$$\gamma_{ad} = \frac{2}{\sum_{\alpha} p_{\alpha} \frac{d_{ada}}{v_{\alpha}}}$$

Equation 4-28

4.3.3.2 Mixed Operations with Pre-emptive Priority to Arrivals

The assessment of unconstrained capacity for mixed mode of operations with pre-emptive priority to arrivals is based on the following four operating rules:

1. Arrivals have a pre-emptive priority over departures;
2. The single runway occupancy rule applies, i.e. only one aircraft can occupy the runway at any time;
3. A departure may not be cleared for take-off if the subsequent arrival is less than a specified distance d_{da} from the runway threshold;
4. Successive departures are spaced at a minimum time separation equal to the weighted average departure service time.

Even though the latter postulate could be avoided, it aims at making the computation simpler against a negligible loss of accuracy.

The sequencing of mixed operations under the rules stated above can be illustrated on a space-time diagram as illustrated in Figure 4-7. In this diagram, the slope of the trajectory at any time is the speed $v(t) = dx(t)/dt$ where x is the coordinate of flight along the approach or departure flight path. A landing aircraft enters the picture at the approach gate. Because approach speed can be assumed to be constant, the trajectory is nearly a straight line until the aircraft touches down. After the aircraft has touched down, it may roll almost to a complete stop before it reaches an exit, or it may turn off on high-speed exit taxiways. This constitutes the arrival runway occupancy time that depends upon approach speed, exit speed, and location of both touch-down and runway exit used.

In this diagram, a departure enters the picture near the threshold (at the line-up position), starts to accelerate uniformly to reach take-off speed, and leaves the straight line departure path at constant first climb speed up to first turn.

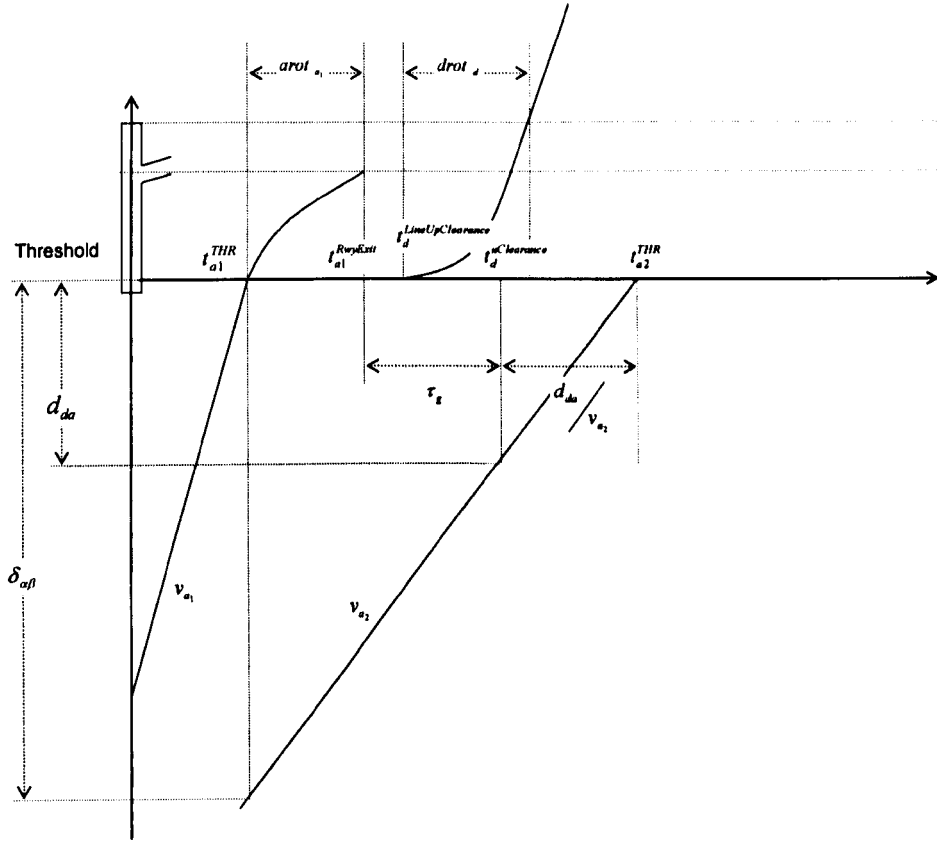


Figure 4-7 – Mixed mode of Operations with Pre-emptive Priority to Arrivals

In this figure,

$t_{a_i}^{THR}$ = time an approach a_i passes over the runway threshold. Because the runway threshold is considered as the reference point, the superscript is most commonly omitted, and $t_{a_i}^{THR} = t_{a_i}$;

δ_{a_i, a_j} = minimum separation minima between successive approaches a_i and a_j ;

$t_{a_i}^{RWYExit}$ = time when the arriving aircraft vacates the runway;

t_d = time when the departing aircraft is cleared to occupy the runway and line-up;

d_{da} = runway locking distance, which is the minimum distance that an arriving aircraft must be from the threshold to release a departure;

$t_d^{uClearance}$ = ultimate time to release a departure without jeopardizing the next approach; it is the very last instant that a departure can be released by ATC;

$arot_{a_i}$ = runway occupancy time for an arrival a_i

τ_g = time gap in which a departure may be released

$drot_d$ = required service time for a departure

Since arrivals are given priority over departures, the arriving aircraft are sequenced at the minimum inter-arrival separation. The sine qua non condition to release one departure between two consecutive arrivals is that the gap τ_g between these arrivals is such that

$$\tau_g = t_d^{uClearance} - t_{a1}^{RWYExit} \geq 0$$

We know that

$$t_{a1}^{THR} = t_{a1}^{RWYExit} - arot_{a1}$$

and

$$t_{a2}^{THR} = t_d^{uClearance} + \frac{d_{da}}{v_{a_2}}$$

Therefore, one departure may be released between a pair of approaches i and j provided that the following condition be met at the runway threshold:

$$\tau_{ij} \geq arot_i + \frac{d_{da}}{v_j}$$

Equation 4-29

If $\overline{\tau_{dd}}$ is the weighted average of the minimum time between successive departures, the required inter-arrival time minima τ_{ij} to release nd_{ij} successive departures between a pair of arrivals i and j is given by

$$\tau_{ij} \geq arot_i + \frac{d_{da}}{v_j} + (nd_{ij} - 1)\overline{\tau_{dd}}$$

Equation 4-30

In other words, the number of departures that can be squeezed between two successive arrivals i and j is defined by

$$nd_{ij} = \frac{\tau_{ij} - arot_i - \frac{d_{da}}{v_j}}{\overline{\tau_{dd}}} + 1$$

Equation 4-31

It can be noted that the equation above is based on the postulate that successive departures between consecutive arrivals are spaced at a minimum time separation equal to the weighted average departure service time.

Let pnd_{ij} be the probability to release nd_{ij} successive departures between a pair of arrivals i and j . The expected number of departures \overline{nd} between a pair of arrivals i and j in the given period of time is therefore defined by

$$\overline{nd} = \sum_{i,j} pnd_{ij} nd_{ij}$$

Equation 4-32

Given that the weighted average value (i.e. expected value) for inter-arrival time is defined by $\sum_{i,j} p_{ij} \tau_{ij}$, the capacity for mixed operations is given by

$$\gamma_{ma} = \frac{\left(1 + \sum_{i,j} pnd_{ij} nd_{ij} \right)}{\sum_{i,j} p_{ij} \tau_{ij}}$$

Equation 4-33

4.3.3.3 Mixed Operations with Pre-emptive Priority to Departures

Although it is less likely to occur especially in the conditions in which departures are continuous, arrivals could be planned to land between two successive departures if the gap between these two departures allows it. In this case, it is postulated that :

1. Departures have a pre-emptive priority over arrivals;
2. Only one aircraft can occupy the runway at any time;
3. Successive arrivals are spaced at a minimum time separation equal to the weighted average arrival service time.

Departures are continuous and therefore sequenced at the minimum interdeparture separation. The sine qua non condition to plan an approach between two successive departures is that the gap between departures fits the following condition :

$$\tau_{ij} \geq arot_k + \frac{d_{da}}{v_k} + drot_i$$

Equation 4-34

where τ_{ij} = temporal differential between the time that leading aircraft of class i is cleared to take-off and the time that trailing departure aircraft of class j is cleared to take-off

$drot_i$ = runway occupancy time of leading departure aircraft of class i

$arot_k$ = runway occupancy time of the released arrival aircraft of class k

d_{da} = minimum distance that an arriving aircraft must be from the threshold to release a departure

v_k = approach speed of the released arriving aircraft of class k

When departures are sequenced in a continuous way, departure separation is governed by the larger of the runway occupancy time and the airborne minima separation δ_{ij}^d , as described by Equation 4-27. Therefore, the condition Equation 4-34 can only be realised if the airborne separation is much greater than the runway occupancy time of the trailing aircraft in such a way that

$$\delta_{ij}^d - drot_j \geq \frac{d_{da}}{v_k} + arot_k$$

Equation 4-35

If $E(t_a)$ is the expected minimum time between successive approaches, the required mean interdeparture time $E(\Delta T_{ij})$ to release na_{ij} successive approaches between a pair of departures i and j is given by

$$E(\Delta T_{ij}) \geq \overline{drot} + \frac{d_{da}}{v} + \overline{arot} + (na_{ij} - 1)\overline{\tau_{aa}}$$

Equation 4-36

Let pna_{ij} be the probability to release na_{ij} successive approaches between a pair of departures. The expected number of departures between a pair of arrivals in the given period of time is therefore defined as

$$\overline{na} = \sum pna_{ij} na_{ij}$$

Equation 4-37

Therefore, the capacity for mixed operations with pre-emptive priority to departures is given by

$$\gamma_{md} = \frac{1 + \sum_{i,j} pna_{ij} na_{ij}}{\sum_{i,j} p_{ij} \tau_{ij}}$$

Equation 4-38

4.3.4 Mathematical Analysis of the Runway Capacity Envelope

In the previous sections, it is formulated how the relationship between the arrival capacity γ_a depends on the various factors that affect capacity, including traffic mix, aircraft fleet mix, runway operating strategy, characteristics of air traffic control system, runway-use configuration and weather conditions. The arrival/departure capacity envelope defines the functional relationship between the interdependent processes of arrivals and departures. The arrival/departure capacity envelope $\gamma_d = (\gamma_a)$ represents a set of theoretical capacity values beyond which the airport cannot accommodate any further traffic if nothing has previously been changed either from an infrastructural point of view or from an operational perspective. Those theoretical capacity values are based on the various equations formulated in the previous section, and as illustrated in Figure 4-8. For lack of continuous function, the capacity envelope $\gamma_d = (\gamma_a)$ can be considered as a piece-wise convex curve, theoretically defined by the five tactics formulated earlier, namely arrivals only, departures only, mixed mode of operations, this latter being split into alternating arrivals and departures,

mixed mode of operations with pre-emptive priority to arrivals, and mixed mode of operations with pre-emptive priority to departures.

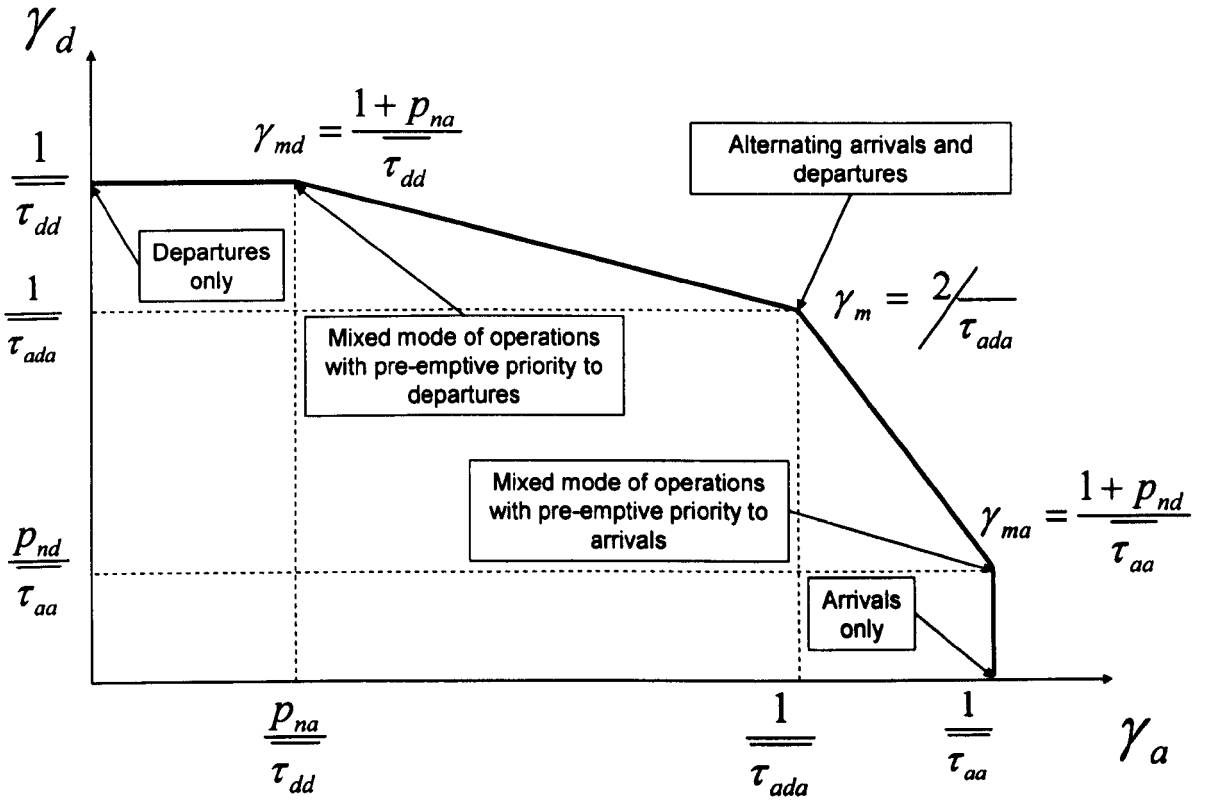


Figure 4-8 – Runway Capacity Envelope

Based on appropriate analytical development, the capacity envelope is formulated through the following set of conditional functions:

$$\left\{ \begin{array}{l} \gamma_d(\gamma_a) = \frac{1}{\tau_{dd}}, \forall \gamma_a \in \left[0, \frac{P_{na}}{\tau_{dd}} \right] \\ \gamma_d(\gamma_a) = \frac{1}{\tau_{ada}} + \frac{\overline{\tau_{ada}} - \overline{\tau_{dd}}}{P_{na} \overline{\tau_{ada}} - \overline{\tau_{dd}}} \left(\gamma_a - \frac{1}{\tau_{ada}} \right), \forall \gamma_a \in \left[\frac{P_{na}}{\tau_{dd}}, \frac{1}{\tau_{ada}} \right] \\ \gamma_d(\gamma_a) = \frac{1}{\tau_{ada}} + \frac{P_{nd} \overline{\tau_{ada}} - \overline{\tau_{aa}}}{\overline{\tau_{ada}} - \overline{\tau_{aa}}} \left(\gamma_a - \frac{1}{\tau_{ada}} \right), \forall \gamma_a \in \left[\frac{1}{\tau_{ada}}, \frac{1}{\tau_{aa}} \right] \\ \gamma_d(\gamma_a) \in \left[0, \frac{P_{nd}}{\tau_{aa}} \right], \forall \gamma_a = \frac{1}{\tau_{aa}} \end{array} \right.$$

Equation 4-39

Literature on runway capacity does not go further than Equation 4-39 from a mathematical point of view. Further analysis of the arrival/departure capacity trade-off leads to the conclusion that the arrival/departure capacity function is **defined everywhere** over the domain $\gamma_a \in \left[0, \frac{1}{\tau_{aa}} \right]$, because $\forall \gamma_a \in \left[0, \frac{1}{\tau_{aa}} \right], \gamma_d(\gamma_a) \in \left[0, \frac{1}{\tau_{dd}} \right]$. However, it is to be mentioned that the last component of Equation 4-39 is not **functional** because several values of $\gamma_d(\gamma_a)$

can correspond to the value $\gamma_a = \frac{1}{\tau_{aa}}$ on that piece of the curve. This is especially true for

segregated modes of operations, when one runway is used for arrivals only whilst the second runway is used for departures only, but this formulation should be corrected in order to be mathematically correct for runway used in mixed mode of operations. Let us consider the subset of Equation 4-39 in which the last component would be ignored; this means that departure capacity $\gamma_d = (\gamma_a)$ is such that $\gamma_d \in \left[\frac{P_{nd}}{\tau_{aa}}, \frac{1}{\tau_{dd}} \right]$ or, in other words, that the image of

the arrival/departure function is $im(\gamma_a) = \left[\frac{P_{nd}}{\tau_{aa}}, \frac{1}{\tau_{dd}} \right]$, for a domain $dom(\gamma_a) = \left[0, \frac{1}{\tau_{aa}} \right]$ remaining

unchanged. Then, the correspondence between arrivals and departures is functional because $\forall x, y \in \left[0, \frac{1}{\tau_{aa}} \right], x = y \Rightarrow \gamma(x) = \gamma(y)$. Because it is defined everywhere and functional,

the arrival/departure capacity relationship $\gamma_d(\gamma_a): \left[0, \frac{1}{\tau_{aa}} \right] \rightarrow \left[\frac{P_{nd}}{\tau_{aa}}, \frac{1}{\tau_{dd}} \right]$ is therefore an

application from a pure mathematical point of view. Mathematical analysis also reveals that

this application is **injective** over the domain $\left[\frac{P_{na}}{\tau_{dd}}, \frac{1}{\tau_{aa}} \right]$, because

$$\forall x, y \in \left[\frac{P_{na}}{\tau_{dd}}, \frac{1}{\tau_{aa}} \right], \gamma_d(x) = \gamma_d(y) \Rightarrow x = y; \text{ it is however not injective over the interval } \left[0, \frac{P_{na}}{\tau_{dd}} \right]$$

because the same value $\gamma_d(\gamma_a) = \frac{1}{\tau_{dd}}$ can correspond too many values γ_a within that

interval $\left[0, \frac{P_{na}}{\tau_{dd}} \right]$. The arrival/departure relationship is also **surjective** because

$$\forall y \in \left[0, \frac{1}{\tau_{dd}} \right], \exists x \in \left[0, \frac{1}{\tau_{aa}} \right] : y = \gamma_d(x), \text{ and in particular over the domain } \left[\frac{P_{na}}{\tau_{dd}}, \frac{1}{\tau_{aa}} \right]. \text{ Because it}$$

is both injective and surjective over the domain $\left[\frac{P_{na}}{\tau_{dd}}, \frac{1}{\tau_{aa}} \right]$, it can therefore be concluded

that the arrival/departure application $\gamma_d(\gamma_a) : \left[\frac{P_{na}}{\tau_{dd}}, \frac{1}{\tau_{aa}} \right] \rightarrow \left[\frac{P_{nd}}{\tau_{aa}}, \frac{1}{\tau_{dd}} \right]$ is **bijective** in mixed

mode of operations. Based on than Equation 4-39, this bijection can be reduced to the two components and formulated as follows:

$$\gamma_d(\gamma_a) : \left[\frac{P_{na}}{\tau_{dd}}, \frac{1}{\tau_{aa}} \right] \rightarrow \left[\frac{P_{nd}}{\tau_{aa}}, \frac{1}{\tau_{dd}} \right] : \gamma_d(\gamma_a) = \begin{cases} \frac{1}{\tau_{ada}} + \frac{\overline{\tau_{ada}} - \overline{\tau_{dd}}}{P_{na} \overline{\tau_{ada}} - \overline{\tau_{dd}}} \left(\gamma_a - \frac{1}{\tau_{ada}} \right), \forall \gamma_a \in \left[\frac{P_{na}}{\tau_{dd}}, \frac{1}{\tau_{ada}} \right] \\ \frac{1}{\tau_{ada}} + \frac{P_{nd} \overline{\tau_{ada}} - \overline{\tau_{aa}}}{\overline{\tau_{ada}} - \overline{\tau_{aa}}} \left(\gamma_a - \frac{1}{\tau_{ada}} \right), \forall \gamma_a \in \left[\frac{1}{\tau_{ada}}, \frac{1}{\tau_{aa}} \right] \end{cases}$$

Equation 4-40

The arrival/departure capacity bijection is **bounded**, the lower bound being represented by

the term $\frac{P_{nd}}{\tau_{aa}}$ and the upper by the term $\frac{1}{\tau_{dd}}$. This piece-wise function is **strictly**

decreasing and **monotonic** over its domain $\left[\frac{P_{na}}{\tau_{dd}}, \frac{1}{\tau_{aa}} \right]$ because

$\forall x, y \in \left[\frac{p_{na}}{\tau_{ad}}, \frac{1}{\tau_{aa}} \right], x < y \Rightarrow \gamma_d(x) > \gamma_d(y)$. The **inflection point** is determined by the alternating

arrival and departure mode, which leads to a change of concavity at the point $\left(\frac{1}{\tau_{ada}}, \frac{1}{\tau_{ada}} \right)$.

4.4 Conclusion

In this Chapter, the safety rules which are considered as fundamental and commonly used for runway operations have been reviewed. The peak-sustainability paradox was formulated, and the conceptual difference between throughput and capacity was stressed. Runway capacity was then synthesized, based on five key operational tactics: arrivals only, departures only, alternating arrival and departure singletons, mixed mode of operations with pre-emptive priority to arrivals, and mixed mode of operations with pre-emptive priority to departures. The runway capacity formulation described the multi-dimensional functional relationship between runway capacity and the various factors that affect it. Finally, the runway capacity envelope was analysed from a mathematical perspective, which enabled the domain of capacity applicability to be determined.

The runway capacity analytical model described in this Chapter is used as the basis for the formulation of the capacity dynamics concepts, as synthesized in Chapter 6. However, to ensure that this analytical formulation of capacity is sufficiently robust and valid from an operational perspective, a case study application is presented, analysed at length, and validated in the next Chapter.

Chapter 5 - Runway System Capacity Analysis: A Case Study

5.1 Context and Scope

5.1.1 The Choice of an Appropriate Case Study

During this research, it was decided to perform a case study in order to illustrate the output of the research and to prove the acceptability of it through its application in the airport operational environment. This Chapter is the first part of that case study.

The choice of an appropriate case study always remains difficult and critical because this choice is based on perception and *a priori* knowledge of the environment. However, four key selection criteria can be identified in order to ensure that the case study will be of value. The first criterion to be considered is the definition of the **objectives** to be achieved. As mentioned in Section 1.2, the ultimate objectives of this case study are twofold: first, to demonstrate the viability of the capacity dynamics concepts in the airport planning process for an existing airport and, second, to illustrate the practicability of the 'airport planning compass'. This Chapter sets up the basis to achieve these objectives by providing a capacity analysis of Brussels National Airport based on operational data and expert validation.

The second criterion is **data availability**. If some data are relatively easy to collect (e.g. traffic sample), others require more effort (e.g. runway occupancy times) and depend on access to the right documentation or data originators (e.g. ATC separation coming from ATC manuals or controllers). Other required data are really difficult, even impossible, to collect with an acceptable level of quality (e.g. aircraft speed on final approach). Appropriate networking with staff at the selected airport is fundamental to ensure access to the right information. As far as Brussels Airport is concerned, this minimum networking exists with both the Airport Operators, BIAC, and the Air Navigation Service Provider, Belgocontrol.

Whilst the second criterion is related to the input to the model, the third criterion directly addresses its output; this third criterion is the **validation ability**. Validating a model with local airport experts requires that the appropriate skill and staff are made available when required, with an acceptable level of willingness and motivation to participate.

Finally, the fourth criterion could be considered as secondary, but is quite important in practice: it is related to **case study practicability**. The questions that need to be raised from that perspective are as diverse as:

- “how easy is it to do?”, in order to minimise the mission costs, or maximise the contact with the staff as soon as required;
- “how easy is it to meet airport experts, and how frequently are they available for brainstorming?”; and
- “are the local parties involved ready to sponsor the research?”.

The airport operators (BIAC) decided to partly sponsor this research, which definitely demonstrates their willingness to cooperate in order to ensure their return on investment. Continuous networking with the Air Navigation Service Provider (Belgocontrol) also enabled appropriate staff to be involved.

Brussels Airport therefore represents *a priori* an ideal candidate for this case study.

5.1.2 Objective

The objective of this Chapter is to undertake a capacity analysis to apply and validate the analytical formulation reported in Chapter 4, while assessing runway system capacity at a major and representative European airport, namely Brussels National Airport. It consists of:

- Collecting up-to-date airport operational data (including traffic pattern, airborne spacing, and aircraft ground performance), for statistical and capacity analysis purposes;
- Reviewing the analysis of the data collected, as well as the preliminary results of capacity analysis with the Airport Operators (BIAC) and ATS providers (Belgocontrol);
- Providing a transparent capacity analysis, and capacity profile, for the various runway operations at Brussels National Airport.

This study has been performed based on a specific baseline scenario, sensitivity analyses and ‘what-if’ scenarios. They have been estimated using the methodology developed in

Chapter 4 of this thesis. The various scenarios and methodology used were reviewed with both the Airport Operator and Air Navigation Service Provider.

As defined and discussed in Section 2.1, this research provides a 'proof of concept' approach to airport capacity analysis, using the most critical airport component from a strategic point of view, namely the runway system. Local considerations such as ATC workload, terminal capacity and landside issues are therefore beyond the scope of this case study, as well as ground traffic on taxiway and apron.

5.1.3 Background information on Brussels National Airport

With its 314,000 movements and 20 million passengers in 1999, Brussels National Airport was one of the airports in ECAC that has experienced a rapid growth in air traffic, due in part to the development of hub operations by Sabena. Brussels National was Europe's 11th busiest airport in terms of passengers, and 5th busiest airport in terms of movements. A report in 1999 forecast that passenger numbers would increase to 35 million at Brussels by 2015.

The events of 11th September 2001 had a dramatic impact on the aviation business world-wide. At Brussels National Airport, these trends were compounded by the bankruptcy of City Bird in October 2001 and, to a greater extent, by the winding up of Belgium's national carrier Sabena in November 2001.

As a result, the total traffic decreased from 326,050 movements in 2000 to 305,535 in 2001, while the number of passengers decreased below the 20 million level (from 21.6 million in 2000 to 19.7 million in 2001). In 2001, Brussels National was the 12th busiest European airport and 46th busiest airport in the world in terms of passenger throughput. Brussels was also the 8th busiest airport in terms of movements in Europe. The number of IFR movements recorded by EUROCONTROL CFMU was 243,965 over the full year 2004. The objective of BIAC, the airport operator, is to bring the airport into the top 5 European airports again.

As shown in Figure 5-1, the runway system at Brussels National Airport (BRU) includes two parallel runways 07L/25R and 07R/25L and one crossing runway 02/20. The two parallel runways have a converging angle of 5 degrees: the perpendicular distance between the extended runway centrelines of 07R/25L and 07L/25R is 1900 meters when measured at threshold 07L whereas it is 1990 m when measured at threshold 25L. In the most commonly

used configuration (25L/R), one of the two parallel runways (25L) is devoted to arrivals only due to noise limitations on its departure path, whilst the other runway (25R) is used in mixed mode of operations.

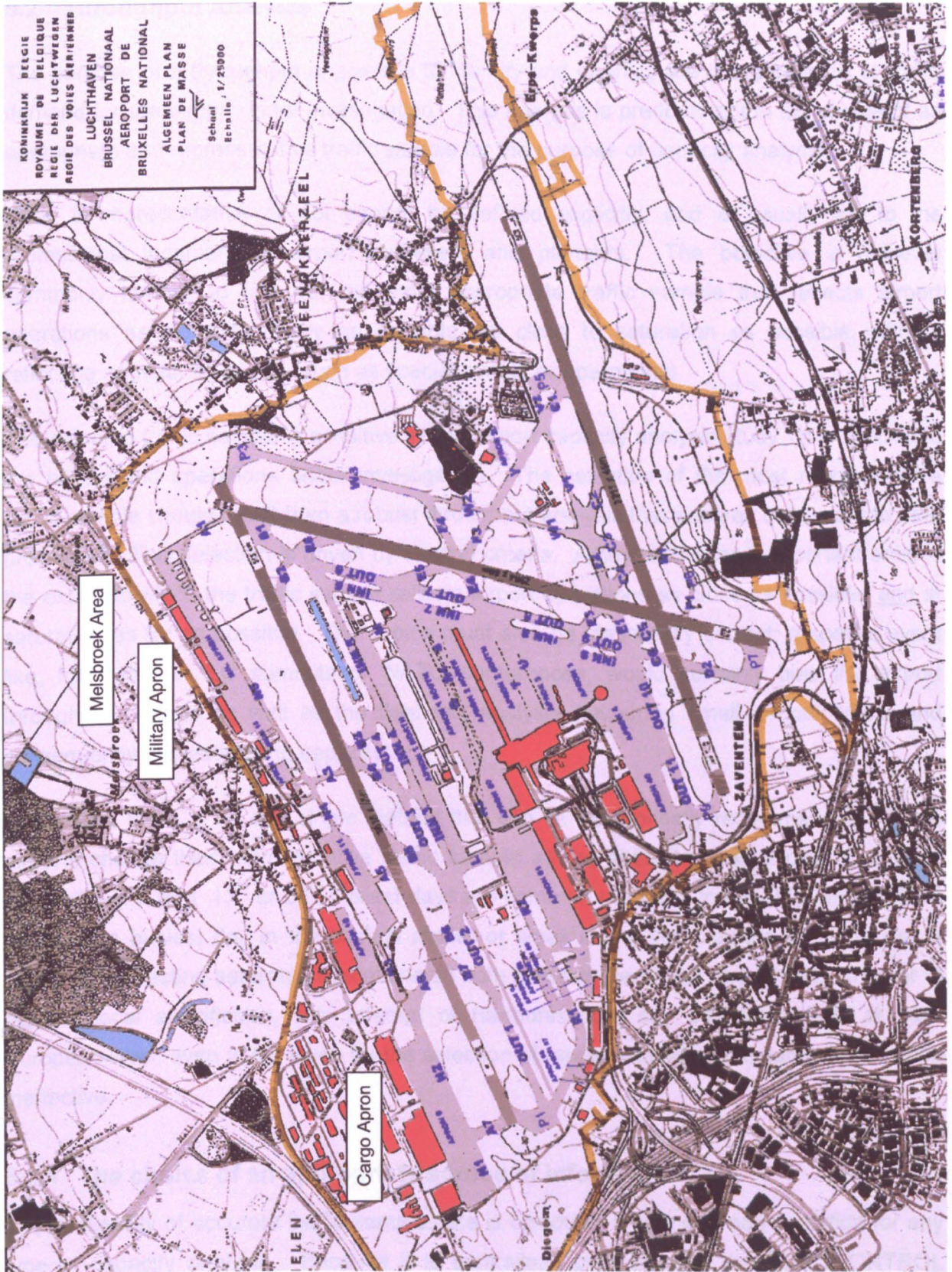


Figure 5-1 - Brussels National Airport Layout

5.2 Throughput Analysis

The purpose of a throughput analysis is to identify and quantify the characteristics of traffic demand for the airport under investigation. This analysis is predominant in the choice of an appropriate and representative traffic sample for the purpose of capacity analysis.

What is representative or not cannot be defined explicitly, and is usually left to the professional judgment of airport modellers and planners. The objective is however commonly known: to find out the most appropriate traffic sample that reflects airport operations as close to reality as possible, as close to saturation as possible, without reflecting unusual situations (such as special events or operations).

The selected traffic sample is sensitive in any airport capacity analysis study. It is specific to the airport and operations under investigation. The selection of the most representative traffic sample should result from a robust throughput analysis that ensures quality of the data processed. This selection is driven by several criteria. Amongst the most important ones is the extent to which the traffic sample reflects airport operations as close as possible, and at saturation as far as possible. The choice must also be statistically correct; a special event like, for instance, EC summits or NATO conferences, would certainly bias the airport throughput records as well as the fleet mix analysis (favouring small aircraft types, and consequently overestimating capacity).

In practice, there is no one single method that can be categorically recommended. Some airports choose their representative traffic sample as the absolute busiest day, or a given percentile of it (e.g. 13th or 30th busiest days are common practices in the UK), whilst others choose the busiest day in the busiest month or week in the year; others prefer to use a virtual day reflecting saturated operations on both landside (terminal) and airside. In order to respect local specificities, any attempt of harmonisation, say standardisation, at pan-European level, even ICAO level, for the selection of representative traffic samples would be ineffective.

5.2.1 The choice of an appropriate source of information

The availability of accurate traffic sample data is obviously a sine qua non condition for any type of capacity analysis. Because it is centralised over Europe, the EUROCONTROL Central Flow Management Unit (CFMU) constitutes an appropriate and valuable source of information.

A statistical analysis of flights recorded by the CFMU shows that a total of 243,965 IFR movements were accommodated by the airport between 1st January 2004 and 31st December 2004. The busiest month was July 2004, with a total of 21,799 IFR movements, closely followed by September, May and June respectively. During these months, more than 21,000 movements were accommodated at the airport on a monthly basis. It is however to be mentioned that the 2004 record is relatively low regarding previous years of operations. Indeed, 326,050 movements were recorded in 2000 whilst the airport accommodated 305,535 movements in 2001.

However, it is questionable whether the CFMU is the most appropriate source of information to extract local traffic samples. Although the CFMU is relatively convenient from a data availability point of view, it is however commonly recognised that some discrepancies can appear between CFMU records and traffic accommodated locally: the CFMU indeed addresses IFR flights only in essence. In addition, it is experienced that some domestic flights, even IFR, might not be transmitted to the CFMU providing they do not affect upper European airspace.

Based on these considerations, local data was requested from Brussels National Airport in order to ensure that the traffic sample used in the scope of this research was as complete as possible. All the flights between 1st September 2003 and 30th June 2005 were collected from the Brussels airport management system (AMS), i.e. 461,231 flights in total. This sample included the following set of information for each flight:

- Call sign
- Aircraft type (ICAO code)
- Movement type (arrival or departure)
- Movement scheduled date and time
- On/off block date and time
- Stand or parking identifier
- Apron used
- Aircraft registration number
- Runway utilised
- Total number of passengers on board

Between 1st January 2004 and 31st December 2004, a total of 252,069 movements were recorded locally, i.e. a discrepancy of 3.3% regarding the CFMU data. In comparison with CFMU data, this increase covers the VFR flights and, to a much lesser extent, military, police

and state¹¹ flights. Figure 5-2 shows the throughput distribution based on BIAC/AMS data as well as the benchmark with the CFMU data.

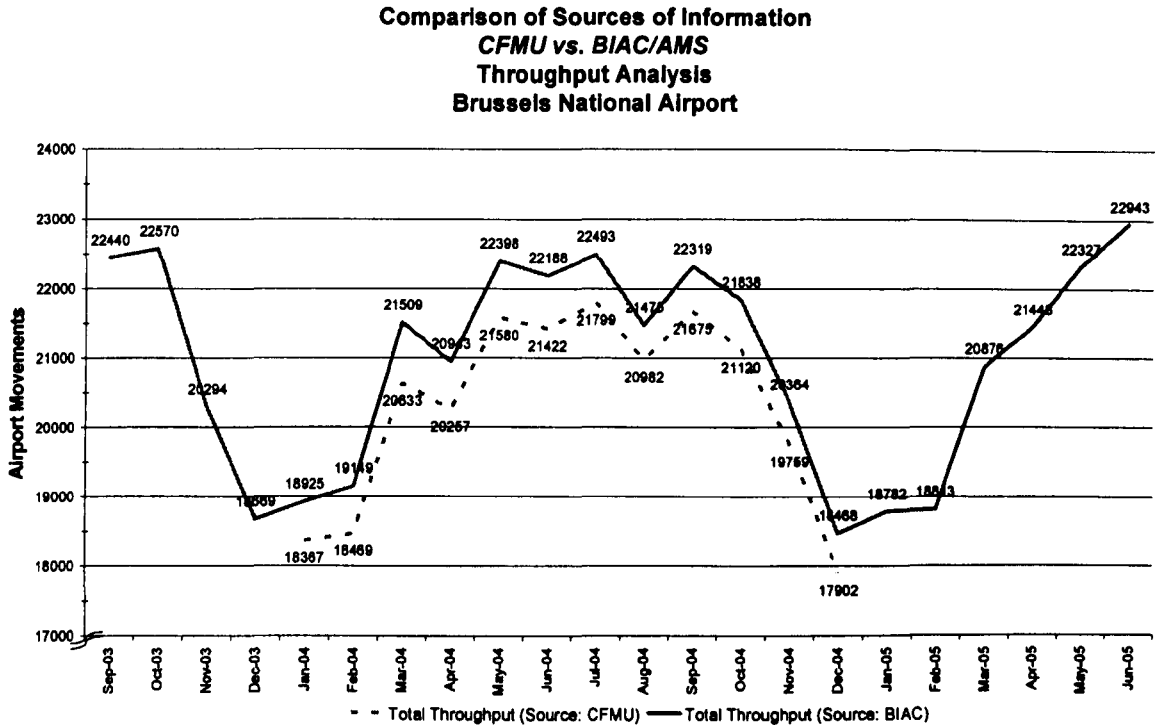


Figure 5-2 – Statistical Analysis for 2004 IFR Movements

The level of time disaggregation is also a major criterion to be considered in the choice of a representative traffic sample, for three reasons. First, there is indeed a challenging trade-off between the achievement of saturated operations and the amplification of factor fluctuation: small time intervals (e.g. 15 minutes) are most likely to capture saturated periods but, on the other side, amplify the potential fluctuation of capacity disrupters, whilst larger time periods (hourly, say daily) tend to smooth peaks while averaging factor dynamics. Second, traffic demand is less likely to stress the airport to its operational limits over long time intervals, but is likely to do so during peak times. Last but not least, the level of time disaggregation is

¹¹ 'State' flights refer to VIP flights to pan-European events (e.g. European summits, NATO key meetings, VIP Visits to Belgian government and monarchy).

also predominant in the estimate of sustainability. Operational sustainability is mainly driven by human factors and endurance. The operational performance level reflected by 15-minutes observations is likely to be unsustainable for several consecutive 15-minutes intervals. On the other side, using observations based on 3-hour time intervals is likely to reflect pure sustainability rather than extreme performance expected at capacity saturation. Using some similitude, time disaggregation makes the difference between endurance and resistance in athletics, or between torque and power in mechanics, the main thing being to know exactly whether one wants to measure the performance of the athlete over a 100-meter sprint or a marathon.

Table 5-1 reports the 20 busiest peaks between 1st September 2003 and 30th June 2005, sorted per order of total movements. A maximum of 886 movements were accommodated on 30 June 2005. Although this might represent a 'very special' day from a statistical point of view, the 20 busiest days are above 840 movements. For hourly time interval analysis, a maximum of 85 movements per hour were accommodated, whilst an average of 81.5 movements per hour happened during the 20 busiest hours. For 30-minute time interval, the average over the 20 busiest peaks is 43.2 movements (per 30 minutes), whilst it is 28.8 movements over the 20 busiest 15-minute peaks¹².

The fact that smaller time intervals amplify the variation of the factors affecting capacity is also illustrated in Table 5-1; the smaller the time interval is, the greater the fluctuation of traffic mix around the traffic mix balance value of 50%, when there are as many arrivals as departures. Because of the endurance-resistance dilemma, empirical data also shows that the peak arrivals and departures observed during 1-hour intervals are likely to be less than half of the peaks observed during 30-minute intervals, and less than a quarter of the observations during 15-minute intervals.

¹² These figures are intentionally not converted into movements per hour in order not to raise hopes for the reader concerning hourly capacity. These flows indeed occurred during smaller time intervals, and are unlikely to be sustainable during greater periods of time.

Daily Peak					Hourly peaks				
Time	Arrivals	Departures	Total	Traffic Mix	Time	Arrivals	Departures	Total	Traffic Mix
Thursday 30 June 2005	434	452	886	49%	23-06-2005 18:00	65	20	85	76%
Wednesday 30 June 2004	439	441	880	50%	27-06-2005 09:00	38	47	85	45%
Friday 17 June 2005	433	442	875	49%	31-08-2004 09:00	35	49	84	42%
Friday 10 June 2005	429	443	872	49%	03-11-2004 09:00	39	45	84	46%
Wednesday 29 June 2005	438	434	872	50%	01-09-2004 09:00	35	48	83	42%
Wednesday 22 June 2005	432	437	869	50%	03-09-2004 09:00	37	45	82	45%
Tuesday 29 June 2004	432	435	867	50%	13-09-2004 09:00	36	46	82	44%
Thursday 23 June 2005	431	434	865	50%	17-09-2004 09:00	34	47	81	42%
Thursday 16 June 2005	439	424	863	51%	08-10-2004 09:00	35	46	81	43%
Wednesday 08 September 2004	433	421	854	51%	12-10-2004 09:00	35	46	81	43%
Friday 20 May 2005	425	428	853	50%	03-05-2005 09:00	32	49	81	40%
Thursday 16 October 2003	424	428	852	50%	28-06-2005 09:00	33	48	81	41%
Wednesday 10 September 2003	426	425	851	50%	12-11-2003 09:00	38	42	80	48%
Wednesday 26 May 2004	427	424	851	50%	12-02-2004 09:00	36	44	80	45%
Wednesday 15 October 2003	431	419	850	51%	07-09-2004 09:00	31	49	80	39%
Friday 18 June 2004	425	425	850	50%	10-09-2004 09:00	37	43	80	46%
Thursday 09 June 2005	432	418	850	51%	20-09-2004 09:00	36	44	80	45%
Friday 28 May 2004	425	424	849	50%	28-09-2004 09:00	33	47	80	41%
Wednesday 15 June 2005	428	420	848	50%	18-10-2004 09:00	35	45	80	44%
Thursday 28 April 2005	421	425	846	50%	23-05-2005 09:00	33	47	80	41%

Peak per 30 minute					Peaks per 15 minutes				
Time	Arrivals	Departures	Total	Traffic Mix	Time	Arrivals	Departures	Total	Traffic Mix
23-06-2005 18:30	40	12	52	77%	23-06-2005 18:30	22	10	32	69%
17-05-2004 08:30	29	16	45	64%	23-06-2005 19:30	12	20	32	38%
29-08-2004 18:30	27	18	45	60%	03-11-2004 09:45	8	23	31	26%
13-09-2004 09:30	16	28	44	36%	29-06-2005 09:45	8	22	30	27%
23-06-2005 19:30	18	26	44	41%	10-09-2004 09:45	9	20	29	31%
19-11-2003 09:30	17	26	43	40%	03-02-2005 18:45	17	12	29	59%
05-12-2003 19:30	18	25	43	42%	24-03-2005 09:45	9	20	29	31%
08-09-2004 18:30	25	18	43	58%	03-09-2004 09:45	8	20	28	29%
30-06-2005 19:00	19	24	43	44%	09-09-2004 09:45	9	19	28	32%
17-11-2003 09:00	27	15	42	64%	16-11-2004 19:30	11	17	28	39%
27-11-2003 09:00	24	18	42	57%	30-11-2004 19:30	9	19	28	32%
03-12-2003 09:00	26	16	42	62%	05-12-2004 18:45	19	9	28	68%
06-05-2004 19:00	17	25	42	40%	03-03-2005 09:45	8	20	28	29%
24-05-2004 19:00	15	27	42	36%	08-03-2005 09:45	7	21	28	25%
03-06-2004 19:00	20	22	42	48%	16-03-2005 09:45	11	17	28	39%
30-06-2004 18:30	27	15	42	64%	17-03-2005 09:45	10	18	28	36%
03-10-2004 18:30	26	16	42	62%	18-03-2005 09:45	10	18	28	36%
20-02-2005 20:00	18	24	42	43%	22-03-2005 09:45	9	19	28	32%
19-05-2005 08:30	23	19	42	55%	03-05-2005 09:45	10	18	28	36%
05-11-2003 09:00	25	16	41	61%	28-06-2005 09:45	9	19	28	32%

Table 5-1 – 20 busiest peaks between 1st Sept 03 and 30th June 05 (Source: BIAC/AMS)

5.2.2 Throughput Analysis per runway configuration

The major runway configuration at Brussels National Airport is a segregated mode of operations, in which RWY 25L is used for arrivals only, whilst RWY 25R is used for departures only. Exceptional landings can be granted on RWY 25R, especially for cargo and military flights, or under special pilot request. This however happens out of peak, when outbound traffic permits.

In order to better reflect the demand for inbound and outbound traffic, a throughput analysis is performed per runway configuration. Table 5-2 shows the 20 busiest peaks for arrivals on RWY 25L, for various time intervals. 43.4 arrivals are accommodated on average over the 20 busiest hourly peaks. This average flow increases to 24.4 and 16.1 arrivals per 30 minutes and 15 minutes respectively. In a similar way, Table 5-3 shows the 20 busiest peaks for departures on RWY 25R, for various time intervals. 48.9 departures are

accommodated on average over the 20 busiest hourly peaks, and this average flow increases to 28.3 and 19.8 departures per 30 minutes and 15 minutes respectively.

Daily Peak		Hourly Peak		Peak per 30 min		Peak per 15 min	
Time	Arrivals	Time	Arrivals	Time	Arrivals	Time	Arrivals
Thursday 30 June 2005	396	23-06-2005 18:00	52	23-06-2005 18:30	32	23-06-2005 18:30	20
Friday 17 June 2005	393	17-06-2005 18:00	47	20-07-2004 18:30	26	17-06-2005 18:45	18
Thursday 02 September 2004	392	09-12-2004 18:00	46	20-06-2004 18:30	25	20-07-2004 18:30	17
Wednesday 25 August 2004	384	18-09-2003 08:00	45	23-07-2004 18:30	25	23-07-2004 18:30	17
Friday 27 August 2004	381	03-09-2004 18:00	45	17-06-2005 18:30	25	03-11-2004 09:00	17
Wednesday 01 September 2004	380	23-07-2004 18:00	44	21-06-2005 18:30	25	11-08-2004 09:00	16
Tuesday 31 August 2004	372	18-08-2004 18:00	43	18-09-2003 08:00	24	17-08-2004 09:00	16
Friday 03 September 2004	372	01-09-2004 18:00	43	17-02-2004 18:30	24	23-08-2004 08:15	16
Thursday 26 August 2004	370	10-09-2004 18:00	43	20-07-2004 09:00	24	31-08-2004 09:00	16
Wednesday 15 September 2004	368	22-06-2005 18:00	43	25-07-2004 18:30	24	03-09-2004 18:30	16
Friday 17 September 2004	366	23-08-2004 08:00	42	03-09-2004 18:30	24	07-03-2005 08:15	16
Friday 20 August 2004	364	27-08-2004 18:00	42	20-06-2005 18:30	24	31-03-2005 08:15	16
Thursday 23 June 2005	364	02-09-2004 08:00	42	23-06-2005 08:30	24	23-06-2005 18:45	16
Tuesday 21 June 2005	363	13-09-2004 18:00	42	29-06-2005 08:30	24	20-06-2004 18:30	15
Wednesday 18 August 2004	362	21-06-2005 08:00	42	17-08-2004 18:30	23	20-07-2004 09:00	15
Tuesday 14 September 2004	357	21-06-2005 18:00	42	01-09-2004 18:30	23	12-08-2004 09:00	15
Tuesday 17 August 2004	356	20-07-2004 18:00	41	10-09-2004 18:30	23	13-08-2004 09:00	15
Wednesday 22 June 2005	354	20-08-2004 18:00	41	03-11-2004 09:00	23	18-08-2004 09:00	15
Tuesday 20 July 2004	348	23-08-2004 18:00	41	09-12-2004 08:30	23	26-08-2004 09:00	15
Friday 24 June 2005	347	31-08-2004 08:00	41	21-06-2005 08:30	23	31-08-2004 08:15	15

Table 5-2 – 20 busiest peaks for arrivals on RWY25L

Daily Peak		Hourly Peak		Peak per 30 min		Peak per 15 min	
Time	Departures	Time	Departures	Time	Departures	Time	Departures
Thursday 30 June 2005	435	24-05-2004 19:00	51	13-01-2004 09:30	30	03-11-2004 09:45	23
Wednesday 30 June 2004	423	03-05-2005 09:00	49	22-01-2004 09:30	29	29-06-2005 09:45	22
Friday 10 June 2005	418	09-05-2005 09:00	49	24-02-2004 09:30	29	08-03-2005 09:45	21
Wednesday 22 June 2005	418	09-06-2005 09:00	49	02-03-2004 09:30	29	03-09-2004 09:45	20
Friday 17 June 2005	415	14-06-2005 09:00	49	15-03-2004 09:30	29	04-09-2004 09:45	20
Thursday 01 July 2004	413	31-08-2004 09:00	48	20-01-2004 09:30	28	21-09-2004 09:45	20
Thursday 24 June 2004	412	01-09-2004 09:00	48	27-01-2004 09:30	28	19-10-2004 09:45	20
Thursday 16 June 2005	409	13-09-2004 19:00	48	28-01-2004 09:30	28	10-12-2004 09:45	20
Wednesday 27 April 2005	407	26-05-2005 09:00	48	10-02-2004 09:30	28	24-03-2005 09:45	20
Wednesday 19 May 2004	406	07-06-2005 09:00	48	12-02-2004 09:30	28	23-06-2005 19:30	20
Friday 20 May 2005	406	29-06-2005 09:00	48	13-02-2004 09:30	28	31-08-2004 09:45	19
Thursday 23 June 2005	406	17-09-2004 09:00	47	17-02-2004 09:30	28	01-09-2004 09:45	19
Friday 07 May 2004	404	28-09-2004 09:00	47	16-03-2004 09:30	28	10-09-2004 09:45	19
Friday 18 June 2004	404	18-04-2005 09:00	47	23-03-2004 09:30	28	14-09-2004 09:45	19
Monday 23 May 2005	404	28-04-2005 09:00	47	25-03-2004 09:30	28	15-09-2004 06:45	19
Wednesday 25 May 2005	404	19-05-2005 09:00	47	28-05-2004 09:30	28	25-09-2004 09:45	19
Wednesday 15 June 2005	404	23-05-2005 09:00	47	04-06-2004 09:30	28	28-09-2004 09:45	19
Friday 19 September 2003	403	10-06-2005 09:00	47	11-06-2004 09:30	28	30-09-2004 06:45	19
Thursday 02 October 2003	402	15-06-2005 09:00	47	02-07-2004 09:30	28	01-10-2004 09:45	19
Wednesday 12 May 2004	402	17-06-2005 09:00	47	13-09-2004 09:30	28	12-10-2004 09:45	19

Table 5-3 - 20 busiest peaks for departures on RWY25R

5.2.3 Selection of an Appropriate Traffic Sample

As far as this case study is concerned, the 20 busiest hours were chosen as a representative traffic sample, as reported in Table 5-1. This choice was driven by the desire to be as close as possible to airport operational saturation.

During those 20 busiest hours, the airport accommodated an average of 81.5 movements per hour during balanced period¹³ whilst inbound throughput on RWY 25L was 43.3 arrivals per hour on average, and outbound throughput on RWY 25R was 47.9 departures per hour on average.

5.2.4 Aircraft Classification

Table 5-4 shows the aircraft classification used for the runway system capacity assessment purposes. This classification is based on the maximum take-off weight as well as the wake turbulence classification recommended in PANS-ATM, Paragraph 16.1.1.

At most European airports, the medium aircraft class is most prevalent in fleet mix analysis. In order to refine the results of the analysis, and because of the large variation in the performance of aircraft in the medium ICAO classification on the ground, this medium class is split into medium turbo-prop and medium jet for the purpose of this project.

As far as wake turbulence classification for the Boeing B757 is concerned, no modification is envisaged at the present by ICAO, and aircraft operators therefore continue to use medium type classification as per their mass weight when filing flight plans. Although its mass weight puts the B757 in the medium class category, controllers at Brussels airport are advised to apply heavy class procedures for this aircraft when it is leading, and medium class when it is trailing. This special class is referred to as Medium-Heavy in the present study.

¹³ For 45% arrival ratio percentage (Pa) on average.

	<i>Aircraft Class</i>	<i>Wake Turbulence</i>	<i>Engine</i>	<i>Example</i>
L	Light	Light	Piston TurboProp	- D228, C500, H25B
MT	Medium-TurboProp	Medium	TurboProp	C91
MJ	Medium-Jet	Medium	Jet	A320's, B737's, F100, MD80
MH	Medium-Heavy	M when Trailing H when Leading	Jet	B757
H	Heavy	Heavy	Jet	A310/330/340, MD11, B747/767

Table 5-4 - Aircraft Classification for Runway System Capacity Assessment

5.2.5 Fleet Mix Analysis

Analysis of the traffic sample also results in the hourly fleet mix distribution. Figure 5-3 shows fleet mix distribution for the top 20 inbound traffic peaks, on RWY 25L. During these top 20 peaks, the traffic was composed of 0.6% light aircraft, 3.0% medium turbo-props, 91.4% medium jets, 1.5% medium-heavy and 3.5% heavies. Fleet mix distribution for the top 20 outbound traffic peaks on RWY 25R is shown in Figure 5-4; the top 20 departure peaks is characterised by 2.7% light aircraft, 6.8% medium turbo-props, 88.6% medium jets, 0.3% medium-heavy and 1.7% heavies on average.

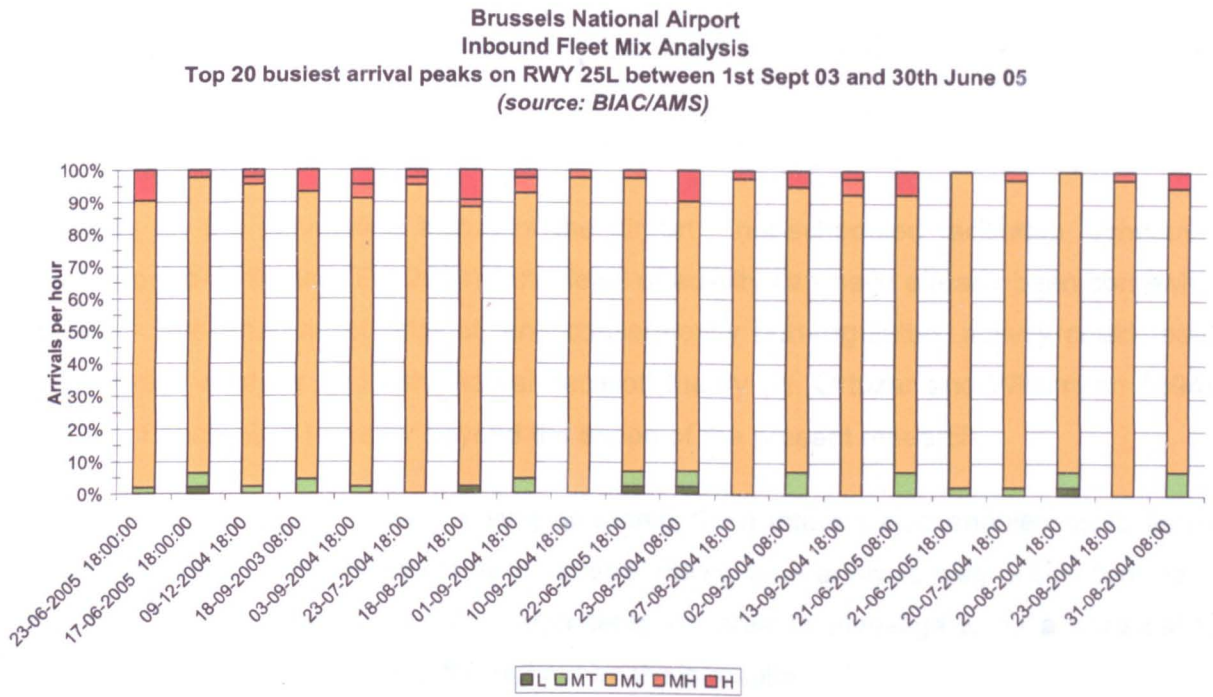


Figure 5-3 – Fleet Mix Analysis for top 20 inbound traffic peaks

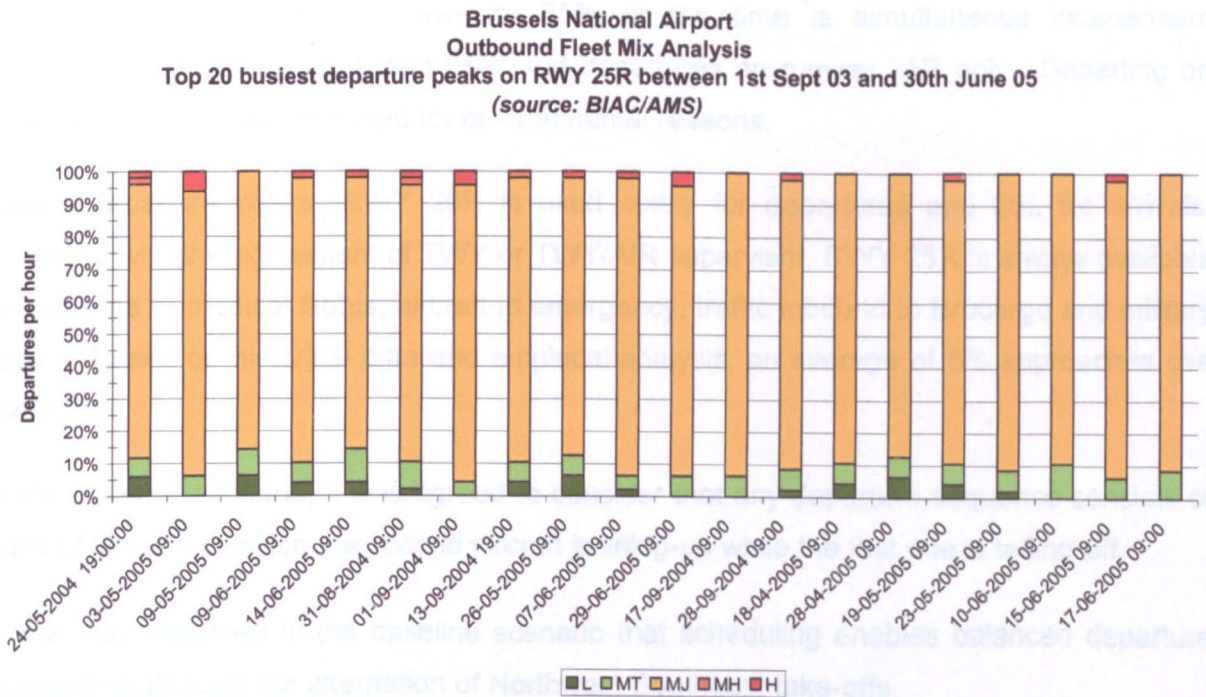


Figure 5-4 – Fleet Mix Analysis for top 20 outbound traffic peaks

The results of this fleet mix analysis will be used as a reference for static capacity assessment.

5.2.6 Limitations

Depending on the scheduling status of the airport - not-scheduled facilitated, scheduled facilitated or co-ordinated (EC 2004) - this level of activity can have already been somewhat regulated. The analysis of original, and consequently non-regulated, activity could result from a market analysis and behavioural decision theory (cf. Ortuzar and Willumsen 1994). This type of analysis is however beyond the scope of the present research.

Using a rolling time (also called moving or sliding time) interval also enables us to better capture saturation. For programming purposes, rolling time analysis was not performed in this research. However, rolling time represents an area to investigate, as a potential to enhance further the quality of the throughput analysis results.

5.3 Capacity Assessment

5.3.1 Baseline Scenario

The runway configuration in use for 85% of the time is simultaneous independent approaches on runways 25L and 25R, and departures on runway 25R only. Departing on runway 25L is usually prohibited for environmental reasons.

During departure peaks, RWY 25R is used solely for departures and 25L for arrivals. However, with the agreement of TWY or TWY/AIR supervisor, RWY 25R is always available for landings of medical flights, aircraft in emergency, traffic inbound to Brucargo and military apron. Based on historical data and empirical analysis, an average of 5% approaches use RWY 25R.

In the baseline scenario, it was agreed to consider that any departure sequence consists of pairs of aircraft, in which the second aircraft is lining-up while the first one is taking-off.

It was also assumed in the baseline scenario that scheduling enables balanced departure sequencing through the alternation of Northwest-Southeast take-offs.

The departures to the first fix identified by HUL is restricted by the requirement to pass 2000 ft on the extended centreline of RWY25R before turning left, in order to ensure separation from a missed approach on RWY25L.

5.3.2 Input Used

5.3.2.1 Approach Speed & Runway Occupancy Time Data Collection

Speeds on final approach and runway occupancy time (ROT) are usually two key factors that may affect capacity.

In order to be as accurate as possible in this assessment, and as close as possible to real airport operations, BIAC and Belgocontrol organised several data measurement exercises for approach speed and arrival and departure runway occupancy times (AROT/DROT). The first data collection exercise was organised in 1999 when Sabena was operating at the airport with about 60% of the traffic. A second data collection exercise took place in September 2002, a third between March and May, and a fourth between September and October 2003. During this latter exercise, more than 360 AROT and 225 DROT observations were collected. The weather conditions during these data collection exercises were not reported, except for one day¹⁴.

During those various exercises, approach speed was collected over the last 4 NM, and extracted from the airport management system (AMS). Arrival runway occupancy time is defined as *the time elapsed between the crossing of the runway threshold, and the time when the aircraft tail is off the runway* (EUROCONTROL 2003). From a safety perspective, this definition is questionable as the aircraft should be beyond the safety shoulder in order that the runway can be considered as free and consequently available for any subsequent runway movement. However, based on a survey performed by EUROCONTROL, this definition reflects operational practices at most European airports, and has therefore been commonly agreed throughout ECAC, based on the fact that an aircraft vacating the runway is rolling and unlikely to be victim of an incident within the few meters of the safety zone. As far as departure runway occupancy time is concerned, it is composed of two key elements:

¹⁴ 26 September 2002, good visibility (3 Km), wet, ceiling decreased from 4000 ft to 1500 ft before 07:30 local time, wind was 290 degrees with a speed ranging from 3 to 7 kts.

- the line-up time, defined as the time elapsed between the time when a departure reaches the active holding stop bar or receives unconditional line-up clearance, whichever is the later, and the time when the aircraft is fully lined up, and
- the take-off time, that is the time elapsed between the time when the departure is fully lined up or when takeoff clearance is given, whichever is the later, and the time when the main gear wheels leave the ground.

In normal operations, and in respect of the single runway occupancy rule, departure runway occupancy time is the sum of line-up and take-off times. However, conditional take-off clearance is a commonly used practice at most saturated airports. In this latter case, a departure is cleared to line up while the preceding aircraft – should it be an arrival or a departure – is still rolling on the same runway. It was reported by Belgocontrol that this procedure is applied once every two departures during the outbound peak, due to departure sequencing. It is also to be recognised that some airports are conservative and, again in respect to the single runway occupancy rule, consider that take-off time expands up to the runway end, instead of wheels-up.

Beyond these considerations, the definitions reported here are adopted by the local air navigation service provider, Belgocontrol, and were used in the scope of those measurement exercises.

The events that determine runway occupancy time were measured manually and visually. Two persons were located in the old ATC Tower and were equipped with synchronised time-event collection software. Although this long and tedious process of data collection does not require sharp skill or expertise, any relaxation of attention and concentration is usually detrimental to the quality of measurements. In addition, the quality is subject to possible parallax problems, due to the fact that the “collectors” were located far away from and not perpendicular to each runway threshold. Although data quality is beyond the scope of this research, only data in strictly delimited arrival and departure peak periods were analysed, and values outside of a 95% confidence interval were excluded. Those values have to be considered with respect to the average fleet mix. Because fewer data are likely to be measured for low fleet mix values of aircraft type, greater deviation is expected.

Table 5-5 reports the values collected, compiled, and provided by BIAC and Belgocontrol for arrival runway occupancy times, on the two runways 25L and 25R, as well as the average approach speed on the final 4 NM. Table 5-6 provides the values for take-off times and departure runway occupancy times. In order to give the reader an order of magnitude of representativeness, the fleet mix is reported in both Table 5-5 and Table 5-6 for inbound and outbound traffic.

	<i>L</i>	<i>MT</i>	<i>MJ</i>	<i>MH</i>	<i>H</i>
Fleet Mix (%)	0.6	3.0	91.4	1.5	3.5
Approach Speed (Kts) on final 4 NM	125	134	140	132	146
AROT 25L (sec)	43.0 (+/- 1.4)	58.3 (+/- 10.5)	50.1 (+/- 7.5)	50.9 (+/- 8.0)	55.7 (+/-8.2)
AROT 25R (sec)	61.1 (+/- 10.0)	60.0 (+/- 9.1)	54.7 (+/- 10.8)	55.0	70.7 (+/- 8.2)

Table 5-5 – Arrival Runway Occupancy Time and Approach Speed Values

	<i>L</i>	<i>MT</i>	<i>MJ</i>	<i>MH</i>	<i>H</i>
Fleet Mix (%)	2.7	6.8	88.6	0.3	1.7
Take-off Time (sec)	33.9 (+/- 16.8)	41.5 (+/-28.5)	41.6 (+/- 14.6)	40.1 (+/- 13.2)	51.6 (+/- 13.1)
DROT (sec)	95.8 (+/- 32.2)	71.3 (+/- 16.4)	87.6 (+/- 29.0)	87.1 (+/-25.4)	92.0 (+/- 26.4)
50% Cond. Line-up clearance (sec)	64.9	56.4	64.6	63.6	71.8

Table 5-6 – Departure Runway Occupancy Time Values

5.3.2.2 ATC Separations

The different ATC separations were provided by ATC experts operating at the airport. These are based on ICAO (1996) safety standards.

The minimum radar separation used is 3 NM, subject to wake vortex separations minima.

		Leading Aircraft				
		L	MT	MJ	MH	H
Trailing Aircraft	L		5	5	6	6
	MT				5	5
	MJ				5	5
	MH				5	5
	H				4	4

Table 5-7 – Wake vortex separation minima (NM).

The minimum departure-arrival separation applied for departures between consecutive approaches in CAT I operations is 6 NM.

Four different cases are considered for inter-departure airborne separations: divergent departure streams (i.e. consecutive right and left turns), successive Northwest departures and successive Southeast departures, with and without full departure airspace constraint.

When successive departures are on divergent tracks, the general rule is to release the following departure as soon as leading departure is wheels up, except:

- when leading departure is slower than following, the 1 minute rule is applied;
- when leading departure is heavy, the 2 minute rule is applied for wake vortex reasons.

The same 1-minute rule is applied to Northwest departures on the same track. If the leading departure is a heavy, then departures are separated by 2 minutes, as shown Table 5-8.

		Leading Aircraft				
		L	MT	MJ	MH	H
Trailing Aircraft	L	60	60	60	120	120
	MT	60	60	60	120	120
	MJ	60	60	60	120	120
	MH	60	60	60	120	120
	H	60	60	60	120	120

Table 5-8 – Inter-departure separation on diverging tracks, and on same track, NW turn, IMC.

With Southeast departures on same track, aircraft climb on the extended runway centreline to 2000 feet before turning left to the two first fixes identified by HUL or CIV. In this case, the 1 minute rule is applicable, as shown in Table 5-9, except:

- if the trailing aircraft is faster than the leading one, the 3 minute rule is applicable;
- two consecutive departures of aircraft in a same class are separated by 1'40";
- if the leading departure is heavy, then departures are separated by 2 minutes.

		Leading Aircraft				
		L	MT	MJ	MH	H
Trailing Aircraft	L	100	60	60	120	120
	MT	180	100	60	120	120
	MJ	180	180	100	120	120
	MH	180	180	180	120	120
	H	180	180	180	120	120

Table 5-9 – Inter-departure separation on same track, SE turn, IMC.

When full departure airspace constraints are considered to the two first fixes HUL and CIV, the above values increase as follows:

- if trailing aircraft is faster than leading, the 5 minute rule is applicable;
- if leading aircraft is heavy , then 5 minute separation is required;
- 2 minute separation otherwise.

		Leading Aircraft				
		L	MT	MJ	MH	H
Trailing Aircraft	L	120	120	120	300	300
	MT	300	120	120	300	300
	MJ	300	300	120	300	300
	MH	300	300	300	300	300
	H	300	300	300	300	300

Table 5-10 – Inter-departure separation for same track, SE turn, departure airspace constraint to HUL and CIV, IMC.

Table 5-10 is reported in order to ensure completeness of the operational procedures for departures. However, it is recognised that these extreme inter-departure separations are avoided as much as possible through appropriate departure sequencing, because they are relatively detrimental to departure capacity. They will therefore be ignored in the capacity analysis that follows.

5.3.3 Capacity Analysis

The methodology proposed calculates unconstrained capacity depending on global factors which are required in order to physically maximise capacity in a safe way. Capacity is equal to the inverse of a weighted-average service time for all aircraft being served. These global factors are the fleet mix and the runway service time defined as either the airborne separation between arrivals and/or departures or the runway occupancy time, whichever is larger.

5.3.3.1 Arrival capacity

Based on Equation 4-14 and Equation 4-19 presented in Chapter 4, inbound operations on RWY 25L are characterised by a weighted average AROT of 50.5 seconds for the inbound fleet mix as reported in Section 5.2.5, whilst the weighted average for airborne inter-arrival separation is 80 seconds. In this case, it is clear that AROT remains less critical than the airborne separation on final approach, and the resulting average in-trail separation time between two successive approaches remains driven by airborne separation, i.e. 1'20". This consequently results in an arrival capacity of 45 arrivals per hour¹⁵. Although the average AROT increases to 55.5 seconds on RWY 25R, it remains less critical than airborne separation as well, and the arrival capacity on that runway is consequently similar.

5.3.3.2 Departure capacity

As formulated in Equation 4-22, departure capacity is determined by departure runway occupancy time (DROT) and inter-departure separation. The average DROT is 64 seconds, considering one multiple line-up operation every two movements, as explained in Section 5.3.2.1.

Based on the inter-departure separations reported in Section 5.3.2.2, on fleet mix during outbound traffic peak reported in Section 5.2.5, and on optimum departure sequence, the average inter-departure time is 74.5 seconds. This results in a departure capacity of 48 departures per hour.

¹⁵ In practice, this is operationally impossible to split flights, or accommodate partial flights. Capacity figures are therefore intentionally rounded to the nearest integer. Nevertheless, the highest accuracy of the various intermediate calculation was maintained in order to ensure the highest quality of the final results.

The reason why the times between arrivals are all larger than between departures is that both pilot and controller cannot make last minute corrections regarding an aircraft on final approach. This means that landings must be planned much more rigorously than departures. Pilot and controllers must allow for any possible event that might occur from the time an aircraft is committed to land until it does land. For instance, if a previous landing aircraft turns off on a high speed exit, the following aircraft is not in a position to take advantage of it. Three conclusions can be made from this fact:

- 1 - arrival capacity will always be less than departure capacity for similar factors other than airborne separation;
- 2 - because landings must be planned more rigorously than departures, due to the little flexibility allowed during final approach, arrival management systems (AMAN) should be more critical than departure management systems (DMAN), providing that the benefit for such systems can be demonstrated; and
- 3 - regarding the business case, it is difficult to justify the development of new runway exits in normal weather conditions, due to predefined fleet mix and unchangeable approach flight profiles, especially for one runway used for arrivals only.

5.3.3.3 Mixed Mode of Operations

5.3.3.3.1 Alternating Arrival and Departure Singletons

Based on a weighted average speed of 140 kts, the average time for the next approach to fly the runway lock distance is 77 seconds, which is greater than the weighted average DROT of 64 seconds. As elaborated in Equation 4-25, capacity in alternating mode is therefore driven by the average AROT of 56 seconds on RWY 25R and the average time required to fly the runway lock distance. This results in an arrival-departure sequence every 133 seconds, or a capacity in alternating mode of 27 arrivals and 27 departures per hour, say 54 movements per hour.

Although it has been explained why AROT has no impact on arrival capacity, one can have a premonition that it does affect alternating capacity, based on Equation 4-25. Indeed, should mixed mode be used on RWY 25L, and because AROT on that runway is reduced to 51 seconds (instead of 56), the time required to accommodate an arrival-departure sequence would be reduced to 128 seconds, that would lead to an increase of alternating capacity from 54 to 56 movements per hour. Although interesting from theoretical and modelling

perspectives, this however remains hypothetical in our case study as RWY 25L may not be used for departures due to environmental constraints.

5.3.3.3.2 Mixed Mode of Operations with Pre-emptive Priority to Arrivals

Based on Equation 4-28, the average number of departures that can be squeezed between two successive approaches, without stretching the inbound flow in any way, is 0.006. Over an hour of operations, in the operational conditions that leads to an arrival capacity of 44.9 arrivals per hour, this means that 0.3 departures can theoretically be squeezed during an hour, which gives a total capacity of 45.2 movements per hour.

5.3.3.3.3 Mixed Mode of Operations with Pre-emptive Priority to Departures

In order to be complete from a formulation point of view, the counterpart to mixed mode operation with pre-emptive priority to arrivals, that is mixed mode operation with pre-emptive priority to departures, has been formulated in Equation 4-38. However, this is operationally unlikely to be able to squeeze arrivals between successive departures without stretching the outbound flow, because inter-departure service time is usually lower than inter-arrival time. In this case study again, it is calculated that it is not possible to squeeze any arrival between departures, and the total capacity in this mode remains identical to departure capacity.

5.3.3.4 Runway System Capacity & Capacity Envelope

In the rest of this thesis, let us adopt the following notation to identify runway-use configurations: <mode of operation><RWY Id>, where <mode of operation> is

- either *a* for “arrivals only”,
- *d* for “departures only”,
- or *m* for “mixed mode operations”.

Therefore, the notation *a25L* represents a runway-use configuration composed of one single runway 25L used for arrivals only. The notation *m25R* represents mixed mode operation on the single runway 25R only, whilst *a25Lm25R* identified the runway-use configuration in which departures are accommodated on runway 25R only, but arrivals are served on the two parallel runways 25R and 25L. It is to be noted that the notations *a25Lm25R* and *m25Ra25L* can be interchangeably used.

Figure 5-5 shows the capacity envelope for the runway system at Brussels National Airport, under the operations and the inputs described in Sections 5.2 and 5.3.2. This capacity envelope is related to the runway configuration a25Lm25R.

Theoretically, it can be seen in Figure 5-5 that capacity ranges from 45 arrivals per hour, up to 99 movements per hour in alternating mode of operation. Departure capacity reaches its ceiling at 48 departures per hour. As mentioned previously, it is impossible to squeeze any approach between successive departures without relaxing pressure on departure flow. The mixed mode operation with pre-emptive priority to departures is thus confirmed to be an academic case, at least for Brussels National Airport. It is however possible to squeeze 0.3 departures per hour between successive arrivals without increasing in-trail spacing.

In a similar way, Figure 5-5 provides the capacity envelopes per runway. The vertical capacity envelope for RWY 25L is characteristic of runways used for arrivals only.

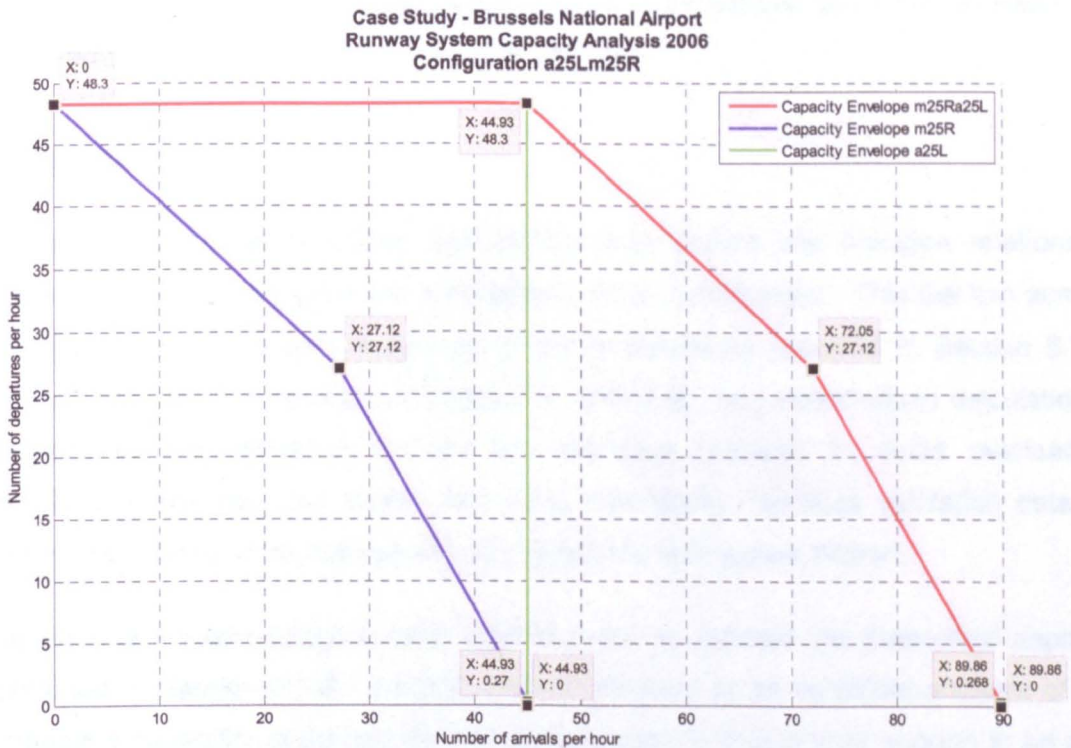


Figure 5-5 – Theoretical Capacity Envelope for RWY Configuration a25Lm25R

This is theoretical only; indeed, the extremes of the capacity envelope are very unlikely to happen. It has also to be recognised that it is relatively unlikely to accommodate 72 arrivals and 27 departures within the same hour from an operational point of view. The fact is that

taking off from RWY 25L is prohibited for environmental reasons. RWY 25R is therefore dedicated to departures. The Cargo area and military apron are however located north of the airport, close to Melsbroek (see Figure 5-1). Therefore, approaches of both cargo and military flights on RWY 25L would lead to runway crossing operations while taxiing, together with extreme taxi-in times. In order to minimize traffic congestion on the ground and to avoid additional ground control workload, landings on RWY 25R are consequently permitted for cargo and military flights only. Although no record was received regarding either the split of traffic per runway or the percentage of cargo and military operations, the proportion of approaches on RWY 25R is estimated to be a maximum 20% by local operational experts.

Based on these considerations, the part of the total capacity envelope for the runway system (m25Ra25L in Figure 5-5) must be limited to a maximum 120% of the approaches permitted on RWY 25L. Consequently, it can be concluded that the hourly capacity during the departure peak (i.e. 25% arrivals and 75% departures) is 53 movements per hour, whilst it is 78 movements per hour during arrival peaks (i.e. 25% departures and 75% arrivals). In alternating mode, the capacity is 60 movements per hour.

5.4 Validation

Chapter 4 provides the intermediate calculations that enable the complex relationship between the various influencing factors and capacity to be synthesised. This Section aims at treating validation on the overall outcomes of the analyses as reported in Section 5.3.3, based on the formulation developed in Chapter 4. However, any intermediate calculation is not addressed in this validation for the two following reasons: to avoid overloading unnecessarily this exercise, but mainly and most importantly, because validation data on intermediate calculations were not operationally available at Brussels Airport.

Two complementary methodologies were used in order to validate the theoretical capacity figures obtained in Section 5.3.3: the first method consists of an empirical analysis of the realised handling capability of the airport, over a time horizon that is long enough to be able to deduce statistically correct conclusions, whilst the second method is based on operational expert judgement and analysis sharing with the local airport operators and ATS experts.

5.4.1 Realised Handling Capability Analysis

As introduced in Section 3.2, the realised handling capability analysis is based on the records of actual accommodated traffic and provides an empirical distribution function as well as empirical capability envelopes for the operational configurations under measurement.

The data collected in the traffic sample (see Table 5-1, Table 5-2 and Table 5-3) are integer-valued numbers of arrivals, departures, and total movements within a predefined period of time. Based on the sample $\{x_1, \dots, x_n\}$ of data collected, the realised handling capability is represented by a probability distribution function and an empirical distribution function. The probability distribution function assigns to every interval of the random variable X - the number of movements for a given set of operational conditions (e.g. runway configuration) - a probability so that the probability axioms are satisfied, and can be seen as a "smoothed out" version of a histogram. The number of accommodated movements X is a discrete random variable that attains values x_1, \dots, x_n with probability

$p_i = p(x_i) = \frac{\text{Number of elements in the sample} = x_i}{n}$. The empirical distribution function is

synthesised by $F_n(x) = \frac{\text{Number of elements in the sample} \leq x}{n} = \frac{1}{n} \sum_{i=1}^n I(x_i \leq x)$, where $I(C)$ is

an indicator function equal to 1 if condition $C = (x_i \leq x)$ is true, 0 otherwise. The empirical distribution function can be synthesized as

$$F(x) = P(X \leq x) = \sum_{x_i \leq x} P(X = x_i) = \sum_{x_i \leq x} p(x_i)$$

Equation 5-1

With the caveat that it is about discrete variables, an empirical distribution function can be assimilated to form a cumulative distribution function (cdf) $F(x) = P(X \leq x)$ describing the probability that a given runway configuration randomly accommodates X number of movements or less than a given threshold x . For a discrete random variable X , the cumulative distribution function consists of a sequence of finite jumps, as illustrated in Figure 5-6; the cumulative distribution function is discontinuous at the points x_i and constant between. The complementary cumulative distribution function (ccdf) is defined by $F_c(x) = P(X > x) = 1 - F(x)$, and provides the probability that a number of movements X greater than a given threshold x are accommodated by the operational configuration under investigation.

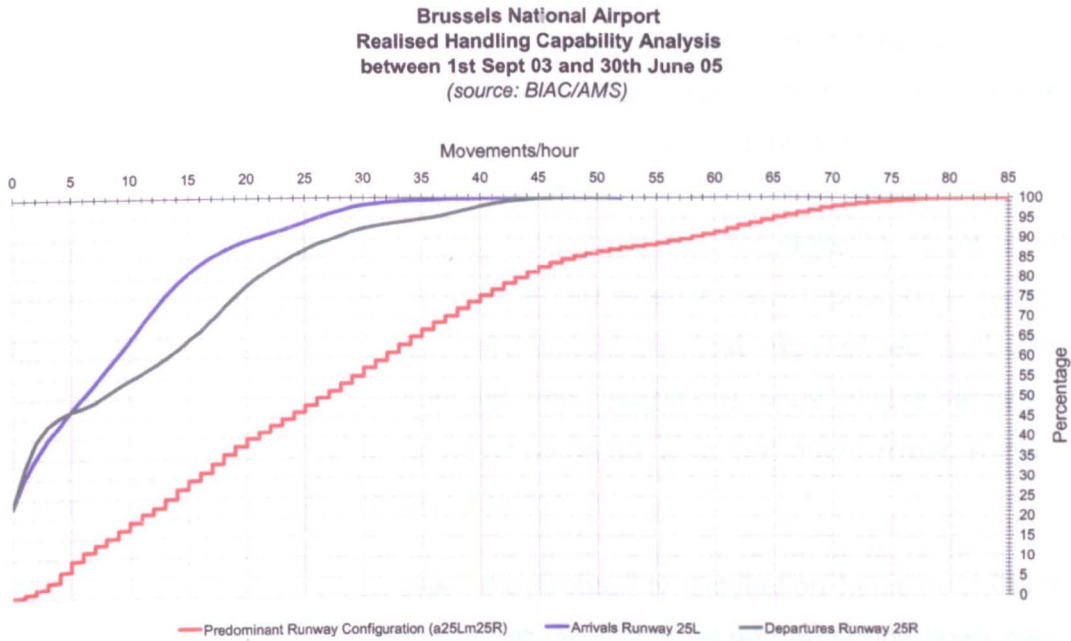


Figure 5-6 – Empirical Distribution of Realised Handling Capability.

Figure 5-6 shows the empirical distribution functions for all the movements accommodated at the airport between September 2003 and June 2005, as well as for the arrivals on RWY 25L and departures on RWY 25R per hour. On this chart, it can be seen that 76 movements per hour or less were accommodated at the airport 99.5% of the time, and 80 movements per hour or less 99.9% of the time (99.9th percentile). The maximum record is 85 movements per hour, that happened only twice over the 22 months of operations under investigation¹⁶. More detailed analysis per runway concludes that RWY 25L accommodated 36 arrivals per hour or less 99.5% of the time, whilst the 99.9th percentile corresponds to 41.4 arrivals per hour. The maximum number of arrivals accommodated by RWY 25L over the time horizon under consideration was 52 arrivals per hour; but this occurred only once over the investigated time horizon. As far as RWY 25R is concerned, the 99.5th percentile corresponded to 44 departures per hour and the 99.9th percentile to 46.5 departures per hour, whilst the maximum departures accommodated was 51, which occurred just once as well.

¹⁶ The hourly throughput of 85 movements was achieved on 23 June 2005 between 18:00 and 18:59 local time, and on 27 June 2005 between 09:00 and 09:59 local time.

A major difficulty of the empirical data analyses lies in the identification of their relative robustness that could be compromised by the possible extremes in the observed data. There might be several reasons for this. These extremes – commonly called *outliers* – can be caused by errors in the original data collection process. For instance, time events might be unintentionally and occasionally omitted by the collectors or processors. Occurrences of airport operations beyond the normal operational capacity limits of the airport for a short period of time can also lead to outlying throughput due, for instance, to an abnormal fleet mix favourable to extreme throughput (especially when a major proportion of movements are by light aircraft), to best performing ATS based on most experienced controllers, and to weather conditions enabling minimum airborne separations; unusual pilot behaviour can also cause abnormally short or long runway occupancy time that might result in low practically realisable capacity during the observed period.

The 2-D plots in Figure 5-7 represent the probability distribution function of the throughput whilst considering the interdependency between inbound and outbound flows over that time horizon under investigation. On this chart, the coordinates of each point show the number of arrivals and departures accommodated at the airport on an hourly basis over that time horizon. Each pair of arrivals and departures is obtained via real observed data on the number of arrivals and departures at the airport during a fixed time interval (60 minutes) between September 2003 and June 2005. The z-value in Figure 5-7 represents the frequency of these events, defined as the number of occurrences of the same pair of values (arrivals and departures per hour) divided by the total number of 1-hour time intervals over the total time period observed. For instance, it can be seen in Figure 5-7 that the runway system enabled 37 arrivals and 15 departures to be accommodated per hour, with a frequency of 0.05605%, i.e. during 900 hours between 1st September 2003 and 30 June 2005. The pair (37; 15) can therefore be considered as a statistically representative value. However, and because the runway system accommodated 85 movements per hour just twice during the period under investigation, the couples (arrival, departure) resulting in 85 movements per hour can be considered as outliers. These outliers are represented by the couples (38; 47) and (65; 20) in Figure 5-7. Each of these outliers appeared just once over 16,056 hourly periods between 1st September 2003 and 30 June 2005, i.e. with a frequency of 0.006228%.

All the more interesting, the empirical distribution of airport/departure interdependency, represented in Figure 5-7, enables both the inbound and outbound peaks to be identified.

This split of the flow into two 'branches' indicates the hub operations characteristic of Brussels National Airport at the time of the study.

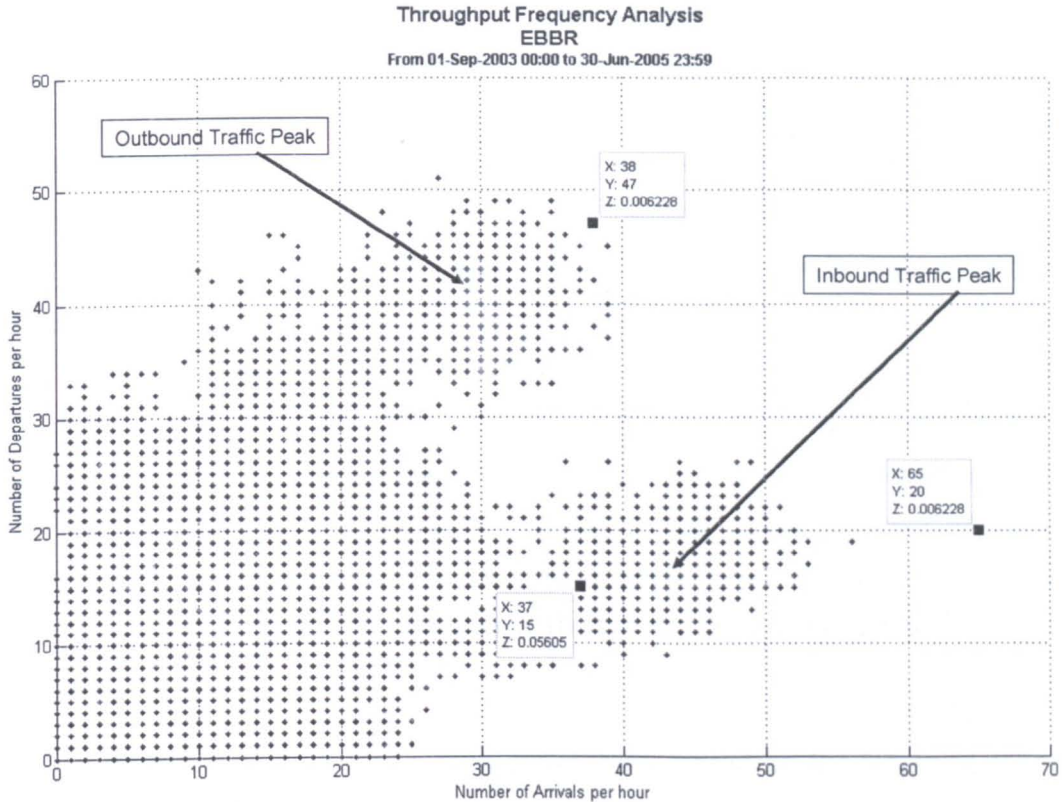


Figure 5-7 – 2-D Representation of the Empirical distribution of airport arrival/departure interdependency

The robustness of the realised handling capability analysis, together with its ability to reflect reality, is directly dependent on its non-sensitivity to outliers. Hence, the identification of appropriate and efficient rejection criteria for the extreme observations, as well as the related rejection algorithms, are paramount and relatively critical as they reflect confidence levels for the results. Those rejection criteria are subject to intensive research in mathematics and their variety determines the variety of estimation algorithms. Rejection criteria can be based on principles as various as ranks of extreme values, proximity of extreme observations to the nearest observations or frequency of occurrences. Being beyond the scope of this research, and in order not to deviate from the core issue of this research, a simple method was used in this analysis in order to reject outliers: the frequency of occurrences and quantiles. Based

on this rejection criterion, the extreme observations that occurred less than a certain number of times within the observed time horizon were rejected.

The choice of appropriate quantiles depends on the length of the time horizon under investigation. When the analysis is based on relatively short time horizons, low percentiles are to be used in order to maintain an acceptable level of confidence. This analysis is based on a very long time horizon covering 22 months of operations, which enables the use of higher percentiles whilst increasing the acceptable level of confidence. It is also obvious that, the lower percentile, the more robust it is. For instance, the 100th percentile is certainly sensitive to outliers, and therefore not robust. The 99.9th percentile is more robust than the 100th percentile, but less than the 99.5th, which is itself less robust than the 99th percentile, and so on. Based on time horizon length, an appropriate level of percentile must be chosen bearing in mind that the ultimate objective of this analysis is to correlate maximum realised handling capability with theoretical capacity. Sustainability is also another factor to be considered in the identification of the appropriate percentile. Lower percentiles are likely to provide estimates of a more sustainable number of operations than higher percentiles, due to frequencies of occurrences. It is not able to sustain extreme peak numbers of operations during long periods of time.

The 99.5th percentile was used and judged appropriate based on the following reason: the previous conclusion on the 99.5th percentile could be expressed inversely, by using the complementary cumulative distribution function. For this specific case, the complementary cumulative distribution function enables us to conclude that the airport accommodated more than 76 movements per hour only 0.5% of the time between September 2003 and June 2005; regarding the hourly basis of the analysis, these 0.5% of the time represent 79 hours, out of a total of 16056 hours. It is therefore statistically correct to reject any value greater than the 99.5th percentile; indeed, those statistical outliers might not be statistically representative of the real capability of the airport.

As specified in Chapter 2 and Section 4.3, the relationship between arrival and departure capabilities (γ_a and $\gamma_d = \theta(\gamma_a)$) depends on the various factors that affect capacity, including runway-use configuration, weather conditions, aircraft fleet mix, runway operating strategy, and characteristics of the air traffic control system. As also specified during the literature review (see Chapter 3), and expressed by Gilbo (1993), the realised handling capability analysis also aims at reflecting major operational and infrastructural restrictions for the entire range of arrival/departure ratios.

Based on the throughput probability distribution analysis, the maximum realised handling capability envelopes – or curves - can be calculated for various percentiles, while taking into account the functional relationship between the interdependent processes of arrivals and departures. Like the capacity envelopes synthesised in Chapter 4, the realised handling capability envelopes are estimated by linearly stretching a piecewise-linear convex curve from the set of observed pairs of arrivals and departures. The maximum realised handling capability envelopes $\gamma_d = \theta(\gamma_a)$ represent a set of (arrivals, departures) values that reflect the operational capability of the airport under investigation, over the time horizon investigated, and irrespective of airport state and operational conditions. As far as our case study is concerned, those envelopes are represented for Brussels National Airport in Figure 5-8, for the major percentiles, namely 90th, 95th, 99th, 99.5th, 99.9th and 100th.

In a similar way to empirical distribution analysis, the robustness (i.e. non sensitivity to outliers) of maximum realised handling capability curves is achieved by rejecting some extreme observations. The same rejection criterion can be used because, if the probability for outliers of the same value to occur more than a representative number of times is negligible, then the envelope that includes those outliers is almost likely not to be representative and robust. In Figure 5-8, the 100th percentile maximum realised handling capability curve is represented on an indicative basis only to illustrate this issue. This curve is likely not to be statistically representative and is definitely not robust because it includes absolute maximum values of observed couples of arrivals and departures. The set of points $\{(0,51), (27,51), (35,49), (38,47), (65,20), (65,0)\}$ that defines that 100th percentile represents a capability envelope that is likely to be an outlier because it includes a set of arrival/departure occurrences that are unlikely to be repeated. The 99.9th percentile maximum realised handling capability curve is determined by a set of (arrivals, departures) couples, that is $\{(0,51), (27,51), (31,49), (38,42), (56,19), (56,0)\}$, and that is also unlikely to be realistic. On the other side, the 99.5th percentile is statistically more robust and insensitive to outliers. The 99.5th percentile maximum realised handling capability curve is determined by a set of (arrivals, departures) couples, that is $\{(0,48), (28,48), (39,37), (56,19), (56,0)\}$, that occurred several times within the time horizon investigated. Based on the same consideration regarding robustness and time horizon length, the 99.5th percentile curve represents a more robust estimate of the maximum capability at the airport.

Practically Realizable Capability Statistical Analysis EBBR

From 01-Sep-2003 00:00 to 30-Jun-2005 23:59

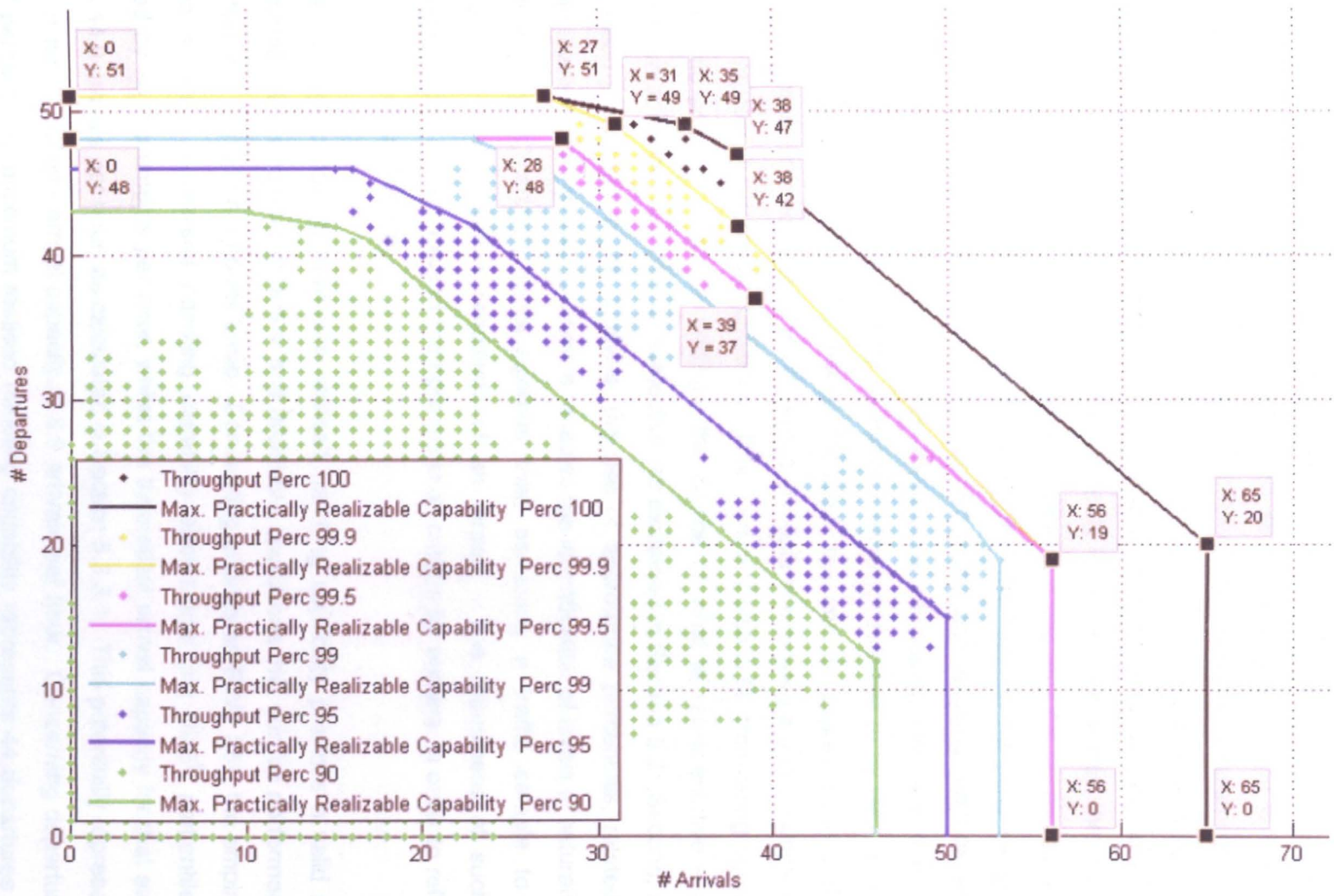


Figure 5-8 – Maximum Realised Handling Capability Envelopes

Our concern is to correlate a confident threshold of realised handling capability x to capacity, based on this empirical analysis. It is to be borne in mind that the (arrival, departure) values shown in Figure 5-7 and Figure 5-8 represent throughput only, and the assumption that their envelope can be interpreted as a capacity envelope is valid for congested airports only, when demand reaches capacity. The capacity assessment based on empirical analysis of real observed data is indeed valid only when it is assumed that, during a given period of time, the observed peak arrival and departure records reflect the airport performance at saturation, i.e. at or near capacity level. In other words, the realised handling capability analysis can be assimilated with capacity if and only if a certain 'close-to-saturation' condition is met. At non-congested airports, the realised handling capability concept cannot reflect airport capacity, due to lack of demand and resulting latent capacity. Based on the 'close-to-saturation' assumption, the curves enveloping the peak data can significantly represent the airport capacity estimates. Although referred to by Gilbo (1993), this close-to-saturation assumption is not synthesized, but can be expressed in various ways. First, the most commonly used methodology consists in choosing a traffic sample that is assumed to represent saturation conditions. This *a priori* choice is far from being rigorous from a scientific point of view. In addition, the choice of what is representative – and consequently what is not - can only be subjective, as explained in Section 5.2. Second, and as it has been performed in this analysis, the use of appropriate percentiles, related to appropriate levels of operational confidence, enables the identification of levels of saturation. This methodology is certainly more rigorous than assuming a traffic sample to be representative of the saturation conditions of an airport. The robustness of such a methodology resides in the choice of the right rejection criteria for outliers, in order to reflect acceptable levels of confidence.

Using the 99.5th percentile of maximum realised handling capability provides a valid and robust estimate of the number of arrival and departure operations that can be performed at Brussels National Airport on a hourly basis. Concerning arrivals on RWY 25L, the empirical distribution analysis of realised handling capability shows that the 99.5th percentile is determined by 36 movements per hour, whilst the theoretical arrival capacity for that same runway is 44.9 arrivals per hour, as calculated in Section 5.3.3.1. This potentially represents a latent - or not operated - arrival capacity of 8.9 arrivals per hour. Concerning departures, the 99.5th percentile of maximum realised handling capability represents 44 departures per hour, whilst the theoretical departure capacity is 48.3 departures per hour. The related

capability/capacity ratio of 91% reflects a relatively great level of saturation and demonstrates the 'close-to-saturation' condition.

5.4.2 Expert-based Judgment and Operational Validation

It is relatively illusory to compare airports with each other, but it is often experienced: which planner has never heard *"My airport should achieve so many movements because that's the capacity of that other airport which has similar layout"*? This shortcut to airport modelling is definitely risky and can only demonstrate a low level of maturity in terms of airport planning. From a probabilistic perspective, it is indeed unlikely to obtain two identical sets of operations – including the same values for all the independent variables on which capacity depends – leading to identical capacity figures for two airports with apparently similar layouts. As a clear example, should traffic demand be considered only, it is relatively unlikely to get identical fleet and traffic mix at various airports. Wiser airport planners and managers commonly recognise that there are no two similar airports in the world. It is all the more true since operational and especially environmental constraints are local considerations. So, a validation of the results provided in the scope of this research based on the values collected at another apparently similar airport would definitely be questionable.

An airport is undoubtedly a complex environment, in the sense that several parties are involved. It is also an obvious fact that no one knows an airport better than the various actors and experts who perform operations and provide services at that same airport. The purpose of expert-based operational validation is therefore to present, share and debate the results of capacity analysis and planning with local experts, with the aim that those people recognise that the output of the analysis makes sense, and is reliable from the operational, planning and capacity management perspectives. Most importantly, the aim of operational validation is to make local actors buy-in to, say approve, the output resulting from the capacity analysis process.

However, it is also obvious those airport stakeholders conduct their business within a shared economic system (the airport itself), that most of the time generates conflicts of interest. The major benefit for airport users (airlines) has been to obtain the maximum number of slots to enable take-off's, whilst the aim of airport operators is to maximise the return on their investment, which is increasingly related to passenger flow through the terminal concessions rather than flight charges. The Air Navigator Service Providers, on their side, aim at

accommodating traffic demand whilst maximising safety with a conservatism and inertia to technical and operational changes.

The results of the modelling process are therefore all the more critical when they are used for the purpose of airport planning, which defines how an airport is expected to evolve as an economic system in the short-, medium- and long-term. In particular, any figure resulting from the capacity analysis process is all the more critical when it is related to a co-ordinated airport. In this latter case, the results of airport modelling are usually used as a basis for discussing and negotiating capacity declaration, which leads to slot co-ordination and scheduling. Therefore, if operational validation is a required step for airport modellers to get their results approved and bought-in by local stakeholders, there is a clear risk to engage with the maze of counter-argumentation put forward by stakeholders due to conflicts of interest, and any other hidden agendas and socio-political considerations. Discovering the limit between "consultation for approval" and "political implications" is the challenge of any operational validation. Any airport modeller who ignores or fails to identify these limits exposes themselves to the rejection of the output of their effort for political reasons, even whether it is valid from both a scientific and operational perspective.

Whilst referring to this specific case study at Brussels National Airport, operational validation was processed with this philosophy, including the key actors at the airport, i.e. the airport operators (Brussels International Airport Company - BIAC), the Brussels Slot Coordination company (BSC) and the Belgian Air Traffic Service Provider (Belgocontrol). The airlines were not consulted because the slot coordinator is performed by BSC. Appendix C provides a brief description of the parties involved. Dr. Ir. Herman Neukermans represented both BIAC and BSC in his successive capacities as Vice-president Strategy at Brussels Airport and Adviser Brussels Slot Coordination. Belgocontrol was represented by Mr. Daniel Goffin, Head of Tower, subsequently Head of Department Strategy and Planning and Chairman of the Capacity Strategic Steering Group (CSSG), Mr. Marc Streckx, appointed Head of Tower in March 2005, and Mr. Eddy Gerits, Chairman of the Brussels Airport Capacity Co-ordination Cell (CCC).

Because of the potential conflicts of interest, a clear risk was identified as soon as this validation process was decided to be performed. Because this case study is undertaken in the scope of our research, and aims at demonstrating the direct applicability and related added value of the capacity dynamics concept to the operational world, any misuse of the resulting figures for slot scheduling or political negotiation needed to be avoided. In order to

mitigate this risk, the various stakeholders (BIAC-BSC and Belgocontrol) were met separately. The validation process was organised into several progress and ad-hoc meetings, during which the data used were reviewed, the progress was reported, and the results debated from an operational perspective. The very first meetings with BIAC and Belgocontrol were relatively informal, and aimed at identifying if the approach used, and the data used for capacity analysis, were endorsed by the two companies. The final meetings were more formally organised and prepared in advance, and the following points were clearly identified:

- Specific goals/objectives/results to be achieved;
- Targeted audience required to achieve those objectives;
- Information and material required to achieve those objectives;
- Possible decisions to be made;
- Proposed action plan, to be implemented by next meeting.

From several brainstorming sessions with Belgocontrol, the following conclusion was presented and agreed by the operational experts. The 99.95th percentile is determined by 36 movements per hour, whilst the theoretical arrival capacity for that same runway is 44.9 arrivals per hour. Although this represents 80% level of saturation, operational justification was reported. It was clearly mentioned by operators that RWY 25R usually accommodates a certain percentage of arrivals, either on pilots' request that can be formulated depending on allocated stands and in order to minimise taxi time (taxi time to Shenghen stands might be reduced from about 30 minutes to 5 minutes!), or for the military and cargo flights whose landing on RWY 25L would lead to RWY 25R crossing operations in order to park on their home base located North of RWY 25R. The allocation of RWY 25R for military and cargo flights is therefore preferred by ATC compared to RWY 25L operations, in order to reduce both controllers' workload and risk of runway incursion and potential incidents inherent to runway crossing operations. This means that the totality of inbound traffic demand is not absorbed by RWY 25L only, which can lead to potential underestimation of the maximum realised handling capability of that runway. The second reason lies in the fact that only one runway is available for departures, whilst two runways can potentially be served for approaches. Departure capacity being the constraining component of capacity at Brussels National Airport, inbound traffic demand itself is therefore led by outbound traffic demand, on the principle that, for a sustainable period of time, any flight coming in should go out, not more not less, i.e. nothing is gained, nothing is lost.

Based on operational experience, the departure capacity estimation of 48.3 departures per hour was accepted by the operational experts. However, it was mentioned that this capacity could be achieved out of the operational constraints for successive departures to the first fixed HUL and CIV (see Table 5-10). This remark is in line with the assumption made during the capacity analysis, which was to ignore these extreme inter-departure separation minima because appropriate departure sequencing enables this sequence type, which is detrimental to departure capacity, to be avoided.

This conclusion from operational experts is in line with the correspondence between departure capability and capacity, as well as with the calculated capability/capacity ratio of 91%. For the same percentile of realised handling capability, the capability/capacity ratio is higher for departures than for arrivals. This stresses the fact that departure capacity is the most constraining capacity component at the airport, because only one runway can be operated for departures – for environmental reasons – whilst two runways are available for approaches.

At the final individual meetings with both Airport Strategy and Belgocontrol, it was clearly concluded that the results of this case study were in line with the results of a previous study performed on 2002 data for both BIAC and Belgocontrol. In this report, it was concluded that *“...when runway 25R is used in mixed mode of operations while runway 25L is used for arrivals only, the runway system capacity for Brussels National Airport ranges from 53 movements per hour during departure peaks to 77 movements per hour during arrival peaks.”* (EUROCONTROL, 2002).

5.4.3 Conclusion

In conclusion, and regarding this specific case study, it has been shown that both the realised handling capability analysis and the expert-based judgement methodology successfully validate the theoretical capacity figures calculated in Section 5.3.

Concerning the validation methodology that was used, additional conclusions and potential improvements can be proposed.

Key criteria were identified in order to attempt a selection of the most appropriate airport candidate for this case study, and it is reported how Brussels Airport was expected to meet these criteria. Although this case study is quite illustrative regarding capacity assessment, it is to be recognised that expectations were too great on Brussels Airport regarding data availability, and the best was made with the level of information available. It is however to be

considered that the level of information detail required in the scope of this case study can only be provided by airport telemetry systems; and there is currently no such airport telemetry systems at European airports. Therefore, even if Brussels Airport does not constitute the ideal case, no other airport was found to be a better illustration.

Should data be available, the historical data can be clustered according to operational conditions experienced at the airport. The same methodology could have been applied in order to provide capacity curves for the various sets of operational conditions that characterise the operations at the airport. This has not been performed in the scope of this research for two reasons: first, this research focuses on the methodology rather than on the aim of covering the full range of operations. It is clear that analysing the full range of operations would have been beneficial for the airport operators and is highly recommended in the scope of an operational capacity analysis. However, there would have been very little additional value from a research point of view and no enhancement of the methodology itself. Second, the data provided by the airport were not detailed enough and did not include any disaggregation per type of operation or airport states.

The quantile-based methodology used to identify close-to-saturation conditions is quite valid for that purpose, although there exists other methodologies that could have complemented this validation if appropriate information was made available. For instance, significant delay records indicate that the airports operate close to or at their operational limits. The delay experienced by airports under certain conditions during peaks can therefore represent a good indication that the '*close-to-saturation*' assumption is valid for this same set of operational conditions. Due to lack of delay data, and most importantly the real causes of delay, this methodology could not be used in this research in order to identify and detect close-to-saturation operations.

As noted in Section 5.4.1, the realised handling capability analysis can be assimilated with capacity if and only if the '*close-to-saturation*' condition is met. For congested airports only, it is reasonable to assume that the historical peak data reflects the maximum operational capabilities and, hence, can be useful for capacity estimation. This condition is however not analytically defined. A percentile-based criterion succeeded in demonstrating close-to-saturation conditions in this analysis, but might not be the optimum criteria for other airports. Further research would certainly be worthwhile in this area.

The realised handling capability methodology, based on empirical distribution analysis, is a macroscopic airport assessment that, in essence, focuses at the airport level and not to any

of its individual components. Because it is based on non-disaggregated airport airside throughput data, the output of the realised handling capability analysis does not enable the identification of the type of constraining airside components, i.e. runway system, taxiways or aprons and stands. On the other side, analytical models, in particular the one synthesised in Chapter 4, are most often specific to one individual component. If the focus is on the runway system, airport modelling analysts should be warned that, because of this scope differential between realised handling capability analysis and analytical modelling of runway system capacity, the results might differ substantially when the weakest and most constraining airport component is not the runway system. As far as this case study is concerned, it has been known *a priori*, based on expert judgement and operational experience, that the runway system is critical at Brussels National Airport, in particular in terms of departure capacity.

Furthermore, this macroscopic concept focuses on the overall airport level and encompasses any kind of constraint and restriction to airport operations, should it be on landside, terminal or airside. Analysts should also be warned such empirical analysis based on air traffic throughput data would not be effective for those airports constrained by terminal capacity issues. The use of empirical analysis in such a case would result in a non-congested airside while neglecting the identification of the real terminal constraint. It is realistic to believe that the constraining airport component (airside or terminal) can be known *a priori* because qualitative expert judgement is sufficient for that purpose. Providing that the constraining airport component (airside or terminal) is known *a priori*, appropriate historical data needs to be identified to ensure the efficiency of the realised handling capability analysis : either air traffic throughput data (if airside is constraining) or passenger flow data (when terminal is constraining).

Realised handling capability analysis is based on historical, and therefore post-operational flight data. In this Chapter, it is demonstrated to be relevant in the scope of strategic air traffic management and related capacity allocation at existing and close-to-saturation airports, for existing operational conditions and airport status. It is nevertheless believed not to be appropriate for the purpose of strategic airport planning, when projected planning options are to be investigated, unless robust and reliable traffic samples can be generated for those projected planning options.

Finally, it needs to be mentioned that this analysis did not intentionally consider rolling time (also called moving or sliding time). Although it is a potential improvement of the

methodology, rolling time usually makes the analysis less traceable and increases the complexity and understanding of the methodology. In other words, the following philosophy applies: better a robust core methodology that leaves space to make minor improvements than an optimised but unstable model.

Chapter 6 - Synthesising the Capacity Dynamics Concepts

"Everything that living things do can be understood in terms of the jiggling and wiggling of atoms."

Richard Feynman, physicist, 1963.

6.1 Context and Scope

6.1.1 General Consideration about Dynamics

The capacity of a system, whatever it is, and airport capacity in particular, is subject to time and space changes. The crux of this research is the analysis of the change capability and amplitude of capacity.

In Section 2.3, airport capacity was shown to be relatively unstable due to the dynamics and related instability of the various factors affecting capacity, rightly named *capacity disrupters*. It has also been concluded that one primordial measure of the intrinsic quality of airport planning – should it be strategic or tactical – definitely lies in the accuracy of predictability. There exists an intrinsic relationship between the factor-based dynamics debated in Section 2.3 and the quality of airport planning. On the specific issue of planning quality assurance, there appears to be little in the way of research reported in the current literature.

In Chapter 3, the review of the literature relative to analytical airport modelling and capacity allocation enables us to conclude that the concept of capacity dynamics as such has never been synthesised from an analytical perspective either by the Scientific Community nor, all the more reason, by the Airport Community. Although it is recognised that the robustness of capacity assessment is strongly dependent on derivatives of the various factors that affect it (Caves and Gillingwater, 2001), the marginal impact of those factors have not been analysed as a whole, which is the focus of this research - the concept of capacity dynamics. Further to ad-hoc consultation and coordination with the Scientific Community, it was concluded in Section 3.7 that the proposed concept of capacity dynamics has not been investigated analytically, even not addressed, although it reveals to be promising in terms of added value to the Airport Community.

In Sections 5.2 and 5.4.1, traffic demand instability was shown through the throughput analysis and related maximum realised handling capability analysis. It is also shown how the appropriate choice of time disaggregation can be the cause of the amplification of either the factor fluctuation or sustainability, the resistance versus endurance dilemma.

Based on those considerations, the objective of this chapter is twofold: first, to synthesise the concept of capacity dynamics. Similarly to the runway capacity model developed in Chapter 4, a case study of which was reported in Chapter 5, the concept of capacity dynamics is based on appropriate analytical modelling, and is demonstrated by using the same case study relative to a representative European airport, Brussels National Airport. Through this first objective, this chapter will contribute to raising awareness of the value of the *a priori* understanding and mastering of the system to be modelled compared to the *a posteriori* analysis modelling habit, as described in the next Section, 6.1.2. The second objective of this Chapter is to demonstrate that the added value of this concept is potentially tremendous in the scope of assistance to both strategic and tactical airport planning. In addition to raising the Airport Community's awareness of the relative instability of airport capacity and the related impact of that instability on slot scheduling and operations, it will be shown how the capacity dynamics concept is a valuable input in order to optimise the prioritisation of potential actions, say options, for capacity enhancement and airport planning.

6.1.2 Review of the Capacity Analysis Process

Many factors can affect and disrupt capacity, ranging from volume and time-dependent pattern of traffic demand, to runway system layout, mixture between inbound and outbound traffic flows, aircraft fleet mix pattern, type of radio-navigational aids, and relatively arbitrary meteorological conditions. All those factors define capacity γ through a complex functional relationship $\theta(f_1, \dots, f_i, \dots, f_n)$.

Based on the review of several airport capacity studies performed by various organisations and airport consultants, the most commonly used process for capacity assessment and analysis fits a classical top-down approach based on a scenario hierarchy. As shown in Figure 6-1, the top-down analysis of a performance indicator under investigation, whatever it is and it might well be capacity in this specific case, consists in assessing this performance indicator while starting from the elementary factors that might affect it. To do so, it is necessary to define the values of those factors for real operations with the aim of assessing the performance indicators as close as possible to reality. Three levels can be distinguished

in the scenario hierarchy: the baseline scenario, sensitivity analyses and 'what-if' scenarios. A **baseline** scenario aims at reflecting airport operations as closely as possible to reality, for the runway system currently in use at the airport. The baseline scenario is also used to calibrate the model and customize it to reflect local specificities if required, as well as to validate the results of the analysis with real operations and expertise from the various local stakeholders. Modelling calibration is a common practice in simulation, not to change the model (the simulator algorithm is not customizable as such), but to build confidence in the input used. Once calibrated, this baseline scenario is the start for further analyses on hypothetical airport planning options, for the purpose of infrastructural and/or operational improvement. Section 5.3 reported a complete example of calibrated baseline scenario for Brussels National Airport, used as a case study in this research. This first step in the scenario hierarchy is commonly referred to as *capacity assessment*.

However, given a calibrated assessment, modellers usually want to go further by analysing the impact of the various factors that might affect the system to be modelled. The *analysis* of a given performance indicator is therefore a step further in the *assessment* on which it is based. **Sensitivity** analyses aim at quantifying the impact of changing a primary input parameter used in the baseline scenario. In contrast, '**what-if**' scenarios aim at quantifying the impact of changing one or several inter-dependent input parameters used in the baseline scenario. The two terms of sensitivity analysis and 'what-if' scenario are often confused by modellers. While the real impact of each individual factor can be identified through sensitivity analyses, it might be relatively difficult to identify the real cause of potential enhancement of a given factor under investigation with 'what-if' scenarios, due to the inter-dependency between the input parameters. In order to be quantified successfully, a given factor must be isolated from all the other factors that potentially affect a given performance indicator; that is the objective of sensitivity analyses compared to 'what-if' scenarios.

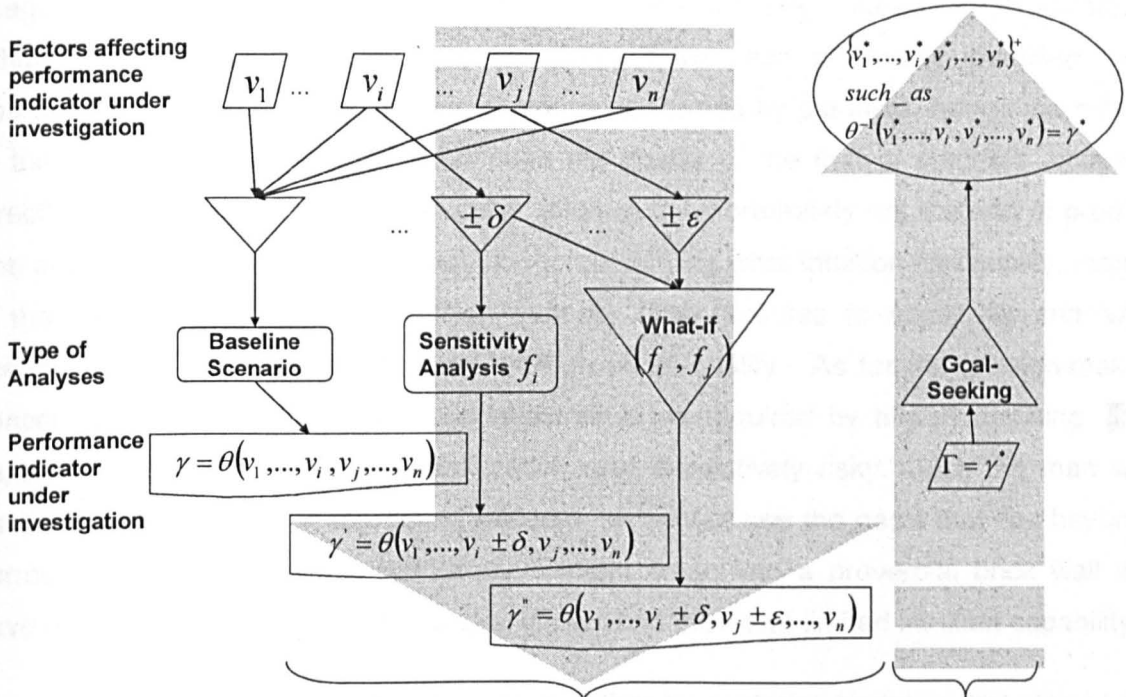


Figure 6-1 – A *posteriori* Analysis of Simulation vs. a *priori* Analysis of Dynamics Modelling

As far as airport modelling and airport planning are concerned, simulation is very often – in many cases, too often - used to analyse those changes. Resorting to simulations should be required only for those systems that consist of a large number of factors and that are so complex that they cannot be analytically synthesized. But, unfortunately too often, the “by-default” and categorical use of simulation by airport modellers reveals their relative incapability of understanding, even worse, mastering the system they attempt to model. Modellers are too often experts in a specific tool (simulator), rather than in the system that this tool models. By using simulations, modellers often prefer to shield themselves from reality, because the effort that they do not spend in a *priori* understanding of the system to be modelled should be all the more spent in a *posteriori* analysis of the simulation results. In addition, the *a posteriori* analysis capability of modellers is legitimately questionable if they cannot demonstrate an acceptable level of a *priori* understanding of the system to be modelled.

As far as sensitivity and ‘what-if’ scenario analyses are concerned, they can only represent planners’ premonitions on how the system could look in some states that are the fruit of their

imagination. In other words, no modeller can model a system state through sensitivity or 'what-if' analyses unless those possible states have been previously identified through appropriate preliminary brainstorming sessions performed by planners, hence the reference to the name "*what-if scenario*". Although the quality of the fruit of planners' imagination directly depends on their vision capability, intuition is unfortunately not the end of prediction. The author's perception is that, in addition to quantifying what intuition can qualify, modelling is the art of predicting what intuition cannot. The recourse to sensitivity and 'what-if' scenarios can, at best, quantify what intuition could qualify. As far as decision-making is concerned, especially for such huge investments as required by airport planning, limiting capacity modelling to intuition quantification only is relatively risky. Like the man who is destined to die of thirst in the desert because he cannot see the oasis that lies beyond the surrounding sand dunes, decision-makers might crash into a proverbial brick wall if they have no means to think, predict and quantify beyond their own limited intuition capability.

Capacity dynamics enables us to go a step further by exploring horizons that stand beyond the top of the mountains that limit the view of whoever stands in the valley. Capacity dynamics aims at predicting what intuition cannot. This capability is a prerequisite to assured planning quality, in such a way that future reality fits as close as possible to what was planned up to 20 years ago. This research aims at promoting the *a priori* understanding of the runway capacity system, in order to identify new horizons that planners' intuition could not imagine, and in order to facilitate *a posteriori* analysis of the results. In order to achieve this objective, a bottom-up approach is therefore promoted. This bottom-up approach consists in analysing the functional relationship between the variables, especially the way their fluctuation affects the system to be modelled. One of the particular uses of this bottom-up approach, and no less interesting, is its ability to identify optima. Especially in mathematics, bottom-up analysis aims at quantifying the values of the primary parameters – inputs – affecting the performance indicators under investigation, in order to obtain a certain value – objective function – of those performance indicators. These bottom-up analyses can be defined as **goal-seeking** analyses (see Figure 6-1).

6.2 Concept of Capacity Dynamics

6.2.1 Capacity State

Originally defined in Newtonian mechanics, the dynamic system concept was developed to describe the time dependence of a point's position in its ambient space. The swinging of a clock pendulum, the flow of water in a pipe, or the number of fish that spring in a lake are all examples of dynamic systems. Later on, the analysis of non-linear dynamic systems led to Chaos Theory. The definition of capacity state is inspired from various theories about dynamic systems.

As developed in Section 2.2 and represented in Figure 2-2, a factor-based approach is a pragmatic way of defining the relationship between various types of capacity (e.g. ultimate, operational) and throughput. The factor-based approach, proposed in this research, is based on the factors that affect the concept to be defined, investigated and modelled, capacity in particular. Therefore, it is also a pragmatic way of defining capacity state. Let $F = \{f_1, \dots, f_i, \dots, f_n\}$ the set including all the factors f_i that affect capacity γ , also called the set of capacity disrupters. The capacity γ is defined by a complex relationship $\theta(f_1, \dots, f_i, \dots, f_n)$ between its disrupting factors. The set of equations that describes this functional relationship were developed in Chapter 4. Let v_i a specific value, usually a real number, which can possibly be assigned to a capacity disrupter f_i . This value v_i belongs to the domain $dom(f_i) = \{\underline{v}_i, \dots, v_i, \dots, \overline{v}_i\}$ of possible values of the capacity disrupter f_i . The value v_i ranges from a minimum possible value \underline{v}_i and a maximum possible one \overline{v}_i .

As represented in Figure 6-2, capacity γ also can take different values and can fluctuate between a minimum value $\underline{\gamma}$ and a maximum value $\overline{\gamma}$ depending on the values v_i assigned to its various disrupters f_i . This set of possible capacity values γ is the image $im(\gamma)$ resulting from the functional relationship $\theta(f_1, \dots, f_i, \dots, f_n)$.

In other words, capacity can be defined as a dynamic system characterised by a given **state**. The capacity state is the vector variable $\vec{S} = (v_1, \dots, v_i, \dots, v_n)$ determined by the collection of values v_i assigned to each factor f_i in such a way that $\gamma = \theta(v_1, \dots, v_i, \dots, v_n) = \theta(\vec{S})$.

Small changes in any of the values v_i into new values v_i' lead to changes of capacity state, from the state \vec{S} into \vec{S}' . Changes in capacity state can, but not necessarily, lead to possible changes of capacity $\gamma = \theta(\vec{S})$ into $\gamma' = \theta(\vec{S}')$. The set of possible states is defined by the possible combination of the values v_i ; this defines the domain of possible states, represented by $dom(\vec{S})$. The domain of possible states $dom(\vec{S})$ is the product of the domains of each factor f_i that contributes to these states, and can be formulated as

$$dom(\vec{S}) = \prod_{f_i} dom(f_i), \forall f_i \in F$$

Equation 6-1

Capacity itself can therefore be defined as a function of n-dimensional capacity state, and the complex relationship that links each other can be represented in a very general way by

$$\theta : dom(\vec{S}) \rightarrow im(\gamma) : \gamma = \theta(\vec{S})$$

Equation 6-2

The number of possible capacity states is defined by the combination of the various possible values of the capacity disrupters, i.e. a combination of the cardinals of the capacity disrupter domains. For example, let us assume a 2-dimensional (say 2-disrupter) system in which the disrupters f_1 and f_2 can be assigned some real values within the domains $dom(f_1) = \{v_1, \dots, v_i, \dots, v_n\}$ and $dom(f_2) = \{w_1, \dots, w_j, \dots, w_m\}$. This 2-disrupter system can take any state $\vec{S}_k = (v_i, w_j)$ such as $\gamma_k = \theta(\vec{S}_k) = \theta(v_i, w_j)$. The maximum number of possible states for the system is therefore defined by n times m . In general, the maximum number of possible states for a n-disrupter system is defined by the product of the cardinals of its n disrupter domains. In other words,

6.2.2 Definition of the Runway Capacity Dynamics Concept

As shown in Figure 6-2, the rate of change of capacity is not necessarily proportional to the rate of change of some specific factors. Indeed, this rate of change might depend upon many factors like the influence of a capacity disrupter compared to another one, in a given capacity state. For instance, a factor might be significantly decreased, and another one slightly increased, that can result in enhanced capacity. In practice, it will be shown in subsequent Sections that an increase of runway occupancy time has absolutely no impact on capacity in some conditions of in-trail spacing minima.

The rate of capacity change also depends on the possible dependency between the various capacity disrupters on each other. For instance, it can be experienced that an increase of approach speed has no impact on capacity in some cases: although higher approach speed contributes to lower in-trail spacing minima, it also and usually entails higher runway occupancy time where the disadvantage blocks out the benefit of lower in-trail time.

Therefore, the rate of capacity change is a complex issue that cannot be analysed rigorously through a top-down approach (sensitivity and/or 'what-if' scenarios, as represented in Figure 6-1), but requires a bottom-up approach based on a *a priori* understanding of the system to be modelled and related analytical formulation. In addition, any modeller who looks for capacity optimisation by groping around for sensitivity and/or 'what-if' scenario analyses can definitely not be sure that the solution he got through simulation represents the *global optimum* rather than some kind of "local" capacity optima.

The capacity dynamics concept attempts to reflect, and quantify the **instantaneous rate of capacity change**, in support of goal seeking, in the mathematical sense of the term. The purpose of the capacity dynamics concept is to provide a performance indication about how quickly the capacity function is able to change at any specific point. In addition, it enables us to formulate the global optimum of capacity, and therefore can be used in support of goal seeking through mathematical optimisation. Figure 6-2 provides a pragmatic approach to capacity state and field of capacity change potential. In theory, the field of capacity change is more complex and is a limited surface rather than a two dimensional plane. This limited surface is characterised by a variable curvature, which the capacity dynamics concept aims at synthesising.

If $F = \{f_1, \dots, f_n\}$ represents the vector variable that is the set of all the factors f_i that impact on capacity γ at various degrees in such a way that $\gamma = \theta(f_1, \dots, f_n)$, then the capacity dynamics with respect to these various factors f_i is defined as the gradient of capacity γ with respect to these factors f_i . This capacity dynamics is noted $\delta(\theta(f_1, \dots, f_i, \dots, f_n))$, $\overline{\delta(\gamma)}$ or $\overline{\delta_\gamma}$, and is formulated as follows:

$$\overline{\delta_\gamma} = \text{grad}(\theta) = \nabla_{f_1, \dots, f_n} \theta(f_1, \dots, f_n); \forall f_i \in F$$

Equation 6-4

Whilst using the Leibniz's notation, capacity dynamics can also be expressed as a column vector whose components are the partial derivatives of the capacity disrupters f_i , as follows:

$$\overline{\delta_\gamma} = \begin{pmatrix} \frac{\partial \gamma}{\partial f_1} \\ \vdots \\ \frac{\partial \gamma}{\partial f_n} \end{pmatrix}$$

Equation 6-5

At any point of the field of capacity change potential, the capacity dynamics vector shows the direction in which capacity changes most quickly. Some measure of the magnitude of this largest capacity change can be represented by a scalar. Let the 2-norm represent this measure. The 2-norm of a vector $\vec{v} = (v_1, \dots, v_i, \dots, v_n)$ corresponds to the Euclidean length and is defined as $\|\vec{v}\| = \sqrt{\sum_i v_i^2}$. In particular, the magnitude δ_γ of the largest capacity change represented by the capacity dynamics vector $\overline{\delta_\gamma}$ is defined as

$$\delta_\gamma = \|\vec{\delta}_\gamma\|$$

Equation 6-6

6.2.3 Interpretation of the Capacity Dynamics Concept

The capacity dynamics concept enables us to describe the measure of the **capacity slope** (or steepness, fall or incline). At any point of the field of capacity change potential, capacity dynamics shows the direction in which capacity changes most quickly. If capacity is expressed with respect to its possible states (see Equation 6-2), then capacity dynamics is the gradient of capacity with respect to those states, and provides the direction to the most promising capacity state that leads to capacity optimum.

$$\vec{\delta}_\gamma = \overrightarrow{grad(\theta)} = \overrightarrow{\nabla_S \theta(\vec{S})}$$

Equation 6-7

The capacity dynamics gradient also indicates how capacity changes in other directions rather than the direction of the largest change. It provides the airport planner with a quantification of the inclination of the field of capacity change potential, at any point, along a given direction of change, i.e. the magnitude of capacity dynamics indicates to airport planners and decision-makers how fast capacity changes in a given planning direction. Indeed, given the surface representing the field of capacity change potential, and given a unit vector on that surface, the inclination (or grade) of the surface in a particular direction is the dot product of the capacity dynamics with that vector. By analogy, consider a walker who attempts to reach the top of a hill, but who does not set off to climb a mountain. The gradient, at the point where the walker stands, points at the direction of the steepest slope; the magnitude of the gradient is 30° in the uphill direction, relatively hard to climb. Rather than using the 30°-slope road which goes directly uphill, the walker takes a path under an angle of 60° with the uphill direction when projected onto the horizontal plane. Then, the slope of the road followed by the walker is reduced to 15°, which is 30° times the cosine of 60°. In summary, **the magnitude of capacity dynamics dotted with a unit vector gives the slope of the field of capacity change potential in the direction of that vector.** In mathematics, this is called the directional derivative.

It is commonly recognised that Air Navigation Service Providers are relatively conservative and do not like significant and fast changes. Another possible use of the capacity dynamics concept is the smooth implementation of capacity enhancement, through its ability to show other directions rather than the direction of largest change. Based on Equation 6-7, capacity dynamics enables the identification of intermediate capacity states to be considered for smooth implementation of capacity enhancement action plans.

Most importantly, for those airports that are operated close to saturation, and close to optimum capacity, capacity dynamics provides airport operators with an indication of the direction of the steepest slope, i.e. how steep capacity decrease can be. Should capacity be declared close to saturation, capacity dynamics provides an indication about how quickly capacity can decrease from the declared capacity, and consequently how quickly delay can grow.

Although the correlation between capacity dynamics and delay should be subject to further research, it is clear that negative capacity dynamics can also indicate some risk of delay growth due to a greater capacity change potential. In contrast, a null capacity dynamics is definitely the sign of **stationary** capacity. A null gradient at a given point of the field of capacity change potential indeed indicates no direction of capacity change. The capacity at that point is therefore **stable** and **robust**, and might be ideal to be considered as a basis for capacity declaration.

This Chapter aims at showing the added value of the capacity dynamics concept through an appropriate interpretation.

6.2.4 Conceptual Definition of Elasticity of Capacity

As defined in Section 6.2.2, capacity dynamics provides absolute values of the magnitude and direction of instantaneous rates of change, at any point of the field of capacity change potential. The provision of such absolute values requires preliminary capacity assessment based on a baseline scenario. This baseline scenario needs to be rigorously calibrated in order to assure quality of the input used and, consequently, the analysis output. Without any calibration, any potential error in the input could have a major impact on the quality of the output.

However, data collection and calibration requires time and effort. Rather than providing airport planners and decision-makers with absolute values of capacity change, it is

sometimes useful to consider the relative impact. For instance, airport planners and operators wish to know by how much capacity can be increased if they change any percent of a factor affecting capacity. In some cases, this information is sufficiently adequate for airport planners and decision-makers, whilst releasing pressure and therefore saving costs on the calibration of the baseline scenario.

In this latter case, the elasticity concept is worthwhile to be considered and applied to airport capacity. The elasticity concept originates from mathematics, and has been used in micro-economics, for the price elasticity of demand in particular. The price elasticity of demand measures the nature and degree of the relationship between changes in quantity demanded of a good and changes in its price. In a similar way, the price elasticity of supply represents a numerical measure of the responsiveness of the quantity of a specific good supplied to a change in price of this specific good alone.

As far as airport capacity is concerned, the arc elasticity of capacity with respect to any of its disrupters f_i between two given points, the so called f_i -arc elasticity of capacity, is noted $\varepsilon_\gamma(f_i)$, $\varepsilon_{\theta(f_i)}(f_i)$ or simply ε_γ , and is defined as:

$$\varepsilon_\gamma = \frac{\%change_in_Capacity_ \bar{\gamma}}{\%change_in_Disrupter_f_i}$$

Equation 6-8

Because it represents a ratio of two percentage changes, the elasticity of capacity is a real number and not a vector in comparison to capacity dynamics.

The elasticity in Equation 6-8 can also be expressed as:

$$\varepsilon_\gamma = \frac{\frac{\Delta\gamma}{\gamma}}{\frac{\Delta f_i}{f_i}} = \frac{f_i}{\gamma} \times \frac{\Delta\gamma}{\Delta f_i}$$

Equation 6-9

When there is a general function between capacity and a disrupter f_i , and when that function is differentiable, then the difference between the two given points can be infinitesimal, and differential calculus can be applied. The point elasticity of capacity concept

can therefore substitute the arc elasticity concept. The f_i -point elasticity of capacity at a given point x of the capacity surface, also simply called the f_i -**elasticity of capacity**, is the ratio of the incremental marginal change of the capacity function with respect to an incremental marginal change of the capacity disrupter f_i , which can be formulated as follows:

$$\varepsilon_{\gamma} = \frac{f_i}{\gamma} \times \frac{\partial \gamma}{\partial f_i} = \frac{f_i}{\theta(f_i)} \times \frac{\partial \theta(f_i)}{\partial f_i}$$

Equation 6-10

or, in Lagrange's notation¹⁷,

$$\varepsilon_{\gamma} = \frac{f_i}{\theta(f_i)} \times \theta'(f_i) = \frac{f_i}{\gamma} \times \gamma'$$

Equation 6-11

Coming back to Equation 6-10, it is to be reminded that $\frac{\partial \log_a x}{\partial x} = \frac{1}{x \ln(a)}$ and

$$\frac{\partial \log_a f(x)}{\partial x} = \frac{1}{f(x) \ln(a)} \times \frac{\partial f(x)}{\partial x}. \quad \text{Therefore, Equation 6-10 can also be reformulated}$$

through the use of a logarithmic transformation, as follows:

¹⁷ To make a slight digression, it is to be noted that the Lagrange's notation is not confusing for the formulation of elasticity, because elasticity of capacity is always a function of one and only one variable. Although Lagrange's notation is simple to use and usually makes formulations lighter for one-dimensional functions, it leads to some loss of information about the variable with respect to which differentiation is formulated for multi-variable functions. In contrast, in partial derivatives, Leibniz's notation allows the variable subject to differentiation to be specified. Because capacity dynamics depends on more than one variable, and because it is worthwhile to maintain this derivative information whilst synthesising capacity dynamics, the Leibniz's notation will be used in the rest of this research.

$$\varepsilon_{\gamma} = \frac{\partial \log \gamma}{\partial \log f_i}$$

Equation 6-12

6.2.5 Interpretation of the Elasticity of Capacity Concept

The f_i -elasticity of capacity enables us the measurement of the nature and degree of the functional relationship between marginal changes in capacity with respect to marginal changes in any factor f_i that impacts on capacity.

In addition, the following rules can be concluded:

- A positive (negative) elasticity of capacity with respect to a capacity disrupter f_i means that any increase in factor f_i leads to an increase (reduction) in capacity.
- When f_i -elasticity of capacity for a capacity disrupter f_i is greater than unity (i.e. $|\varepsilon_{\gamma}| > 1$), then the percentage change in capacity is greater than that in the disrupter f_i . In other words, a slight or relatively small change in the factor under investigation leads to a sharp and large change in capacity. In this case, capacity is said to be **elastic** with respect to this particular factor that affects it.
- When the f_i -elasticity of capacity is undefined, any change in the factor affecting capacity, no matter how small, will cause capacity to drop to zero. Capacity is then considered as **perfectly elastic** with respect to a particular capacity disrupter. The capacity curve consequently approaches a vertical straight line.
- When the percentage change in capacity is equal to that of a particular capacity disrupter, then the elasticity of capacity with respect to that disrupter is **unit** (or **unitary**) **elastic** (i.e. $|\varepsilon_{\gamma}| = 1$). When capacity is unitary elastic, the capacity curve is a rectangular hyperbola.
- Capacity is considered **inelastic** with respect to a particular capacity disrupter when capacity does not change significantly with respect to significant fluctuation of this

capacity disrupter. In this case, the f_i -elasticity of capacity for a capacity disrupter f_i is smaller than one (i.e. $|\varepsilon_y| < 1$).

- At the other extreme, when the f_i -elasticity of capacity for a capacity disrupter f_i is null (i.e. $|\varepsilon_y| = 0$), any fluctuation of the capacity disrupter under consideration has absolutely no impact on capacity. In this latter case, capacity is said to be **perfectly inelastic** with respect to that particular factor, and the capacity curve is a horizontal straight line.

In Equation 6-8, both the denominator and numerator of the fraction are percent changes. One of the advantages of the elasticity of capacity concept is that it is a dimensionless number. Elasticities of capacity for various factors can therefore be compared with each other in order to identify the most promising changes, even if the original calculations are performed using different units.

6.3 Analytical Formulation of Elasticities of Capacity and Capacity Dynamics

6.3.1 Methodology Used

Section 6.2.1 set the scene by defining the concepts of capacity state and field of capacity change potential (capacity surface), before defining the two concepts of capacity dynamics and elasticity of capacity in Sections 6.2.2 and 6.2.4. As formulated in Equation 6-5 and Equation 6-10, these two concepts are based on the differentiation of capacity with respect to the factors that might disrupt it. These factors were identified and described at length in Section 2.3, and represented in a relatively vague relationship diagram, in Figure 2-4. The complex relationship $\theta(f_1, \dots, f_i, \dots, f_n)$ between the various capacity disrupters was synthesized in Chapter 4 through the analytical formulation of runway capacity. Further analysis of the analytical formulation also enabled the various capacity disrupters to be ordered and prioritised according to their real impact on capacity.

Based on the relationship diagram in Figure 2-4, an influence analysis process results in the runway capacity influence diagram as shown in Figure 6-3.

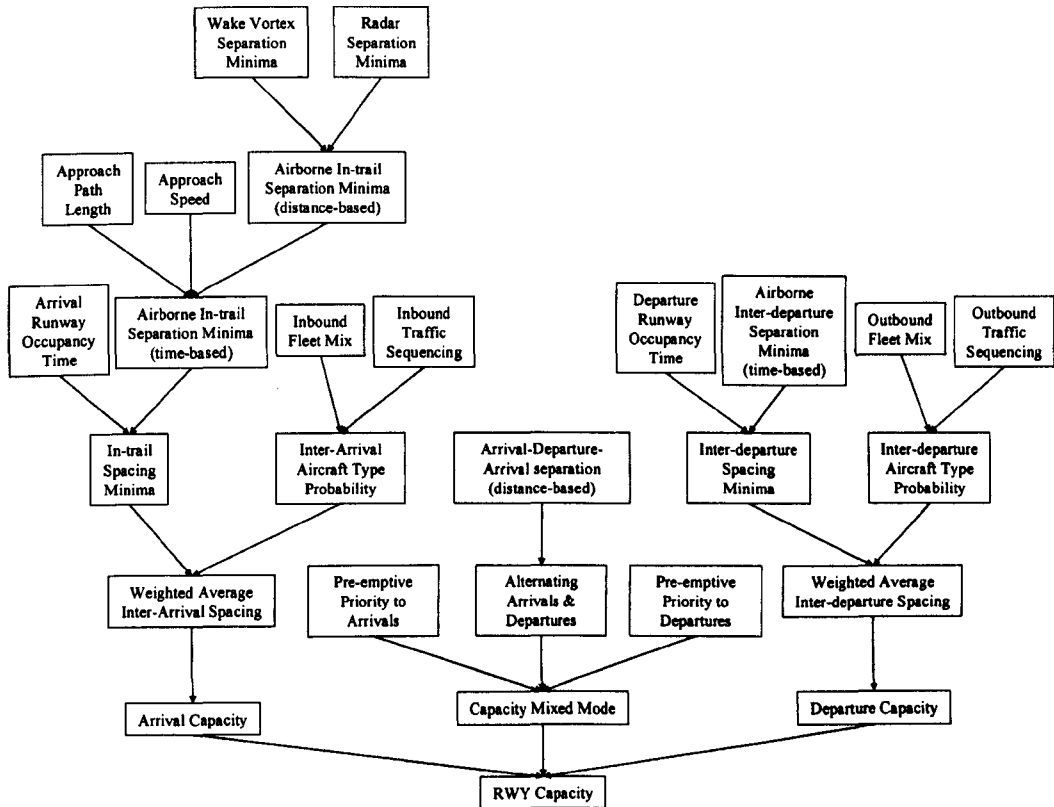


Figure 6-3 – Runway Capacity Influence Hierarchy

The formulation and analysis of the capacity dynamics concept and the various elasticities of capacity require an appropriate methodology that can be based on the capacity influence diagram. This diagram is created in such a way that it goes from the fully dependent variable at the bottom (i.e. runway capacity) up to independent variables at the top of the hierarchy (i.e. the leaves on the tree analogy), through variables that are dependent with varying degrees.

For instance, the independent variable wake vortex has fundamentally nothing to do with runways and is defined by aerodynamic laws only. But, indirectly, wake vortex impacts on capacity, and that is the reason for which it is subject to specific ICAO (1996) recommendations. Another example is distance-based in-trail separation minima that is dependent of wake vortex and radar separation minima, but which is fully independent of approach speed. Two different factors that affect capacity are linked to each other when there exists a certain degree of dependency between them; this dependency is described by one of the functional relationships formulated in Chapter 4. The links between variables are

directed in order to indicate the dependency. A variable is linked to a set of factors through arrows that originate from each of these factors and end at this variable. This means that this variable is dependent on all those factors. Each link could be labelled with the appropriate analytical equation in Chapter 4. These labels are however not represented in Figure 6-3 in order to avoid overloading the figure, but will be presented during the formulation of the two concepts in the next Section.

In the capacity influence diagram, it can be seen that runway capacity directly depends on its capability to exclusively accommodate arrivals or departures, but also to face the arrival-departure mix trade-off with various tactics (pre-emptive priority to arrivals, alternating arrivals and departures operations, pre-emptive priority to departures). At a higher level within the influence hierarchy, arrival capacity depends itself from a weighted average inter-arrival spacing defined by both in-trail spacing minima and probability of consecutive landing aircraft types, and so on and so forth. More importantly, it can be seen that arrival runway occupancy time does not directly affect runway capacity, but indirectly through in-trail spacing minima. This just so happens that in-trail spacing minima is also dependent on other factors and, as mentioned previously, it might well be the case that one of these other factors counteracts the indirect impact of runway occupancy on capacity. This influence diagram therefore raises decision-maker's awareness that it is certainly not wise rushing to hasty conclusions, such as *"Arrival runway occupancy time is always predominant in runway capacity"* or, even worse, *"New runway exits with optimal location are always good for capacity"*. The capacity dynamics concept enables us to refine that kind of decision, and make it more robust.

The methodology proposed to synthesize capacity dynamics and the various elasticities of capacity is based on the bottom-up analysis of the capacity influence hierarchy. Let v_m^i any variable at a level i of the influence diagram, and let assume that this variable v_m^i is affected by two other variables v_n^{i+1} and v_o^{i+1} at the level $(i + 1)$ of the influence diagram. There exists therefore two directed links (arrows) on the influence diagram: a first one from v_n^{i+1} at the level $(i + 1)$ towards v_m^i at a level i , and a second one from v_o^{i+1} to v_m^i . This dependency can be defined by a functional relationship $v_m^i = \theta(v_n^{i+1}, v_o^{i+1})$. The dynamics of the variable v_m^i can be formulated by applying Equation 6-4 and differentiating the function

$v_m^i = \theta(v_n^{i+1}, v_o^{i+1})$. More specifically, the dynamics of the variable v_m^i is expressed by the vector

$$\overline{\delta(v_m^i)} = \overline{\nabla \theta(v_n^{i+1}, v_o^{i+1})} = \begin{pmatrix} \frac{\partial \theta(v_n^{i+1}, v_o^{i+1})}{\partial v_n^{i+1}} \\ \frac{\partial \theta(v_n^{i+1}, v_o^{i+1})}{\partial v_o^{i+1}} \end{pmatrix}$$

Equation 6-13

The two elasticities $\varepsilon_{v_m^i}(v_n^{i+1})$ and $\varepsilon_{v_m^i}(v_o^{i+1})$ of the variable v_m^i with respect to v_n^{i+1} and v_o^{i+1} can be formulated by applying Equation 6-10, i.e.

$$\begin{cases} \varepsilon_{v_m^i}(v_n^{i+1}) = \frac{v_n^{i+1}}{v_m^i} \times \frac{\partial \theta(v_n^{i+1}, v_o^{i+1})}{\partial v_n^{i+1}} \\ \varepsilon_{v_m^i}(v_o^{i+1}) = \frac{v_o^{i+1}}{v_m^i} \times \frac{\partial \theta(v_n^{i+1}, v_o^{i+1})}{\partial v_o^{i+1}} \end{cases}$$

Equation 6-14

At the next iteration of the analysis of the influence diagram, let us assume that the variable v_o^{i+1} can itself be affected by two other variables v_p^{i+2} and v_q^{i+2} at the level $(i + 2)$, through a functional relationship $v_o^{i+1} = g(v_p^{i+2}, v_q^{i+2})$. In a similar way, both dynamics of the variable v_o^{i+1} and elasticities of v_o^{i+1} with respect to v_p^{i+2} and v_q^{i+2} can be formulated as follows:

$$\overline{\delta(v_o^{i+1})} = \overline{\nabla g(v_p^{i+2}, v_q^{i+2})} = \begin{pmatrix} \frac{\partial g(v_p^{i+2}, v_q^{i+2})}{\partial v_p^{i+2}} \\ \frac{\partial g(v_p^{i+2}, v_q^{i+2})}{\partial v_q^{i+2}} \end{pmatrix}$$

Equation 6-15

and

$$\begin{cases} \varepsilon_{v_o^{i+1}}(v_p^{i+2}) = \frac{v_p^{i+2}}{v_o^{i+1}} \times \frac{\partial(g(v_p^{i+2}, v_q^{i+2}))}{\partial v_p^{i+2}} \\ \varepsilon_{v_o^{i+1}}(v_q^{i+2}) = \frac{v_q^{i+2}}{v_o^{i+1}} \times \frac{\partial(g(v_p^{i+2}, v_q^{i+2}))}{\partial v_q^{i+2}} \end{cases}$$

Equation 6-16

The purpose of the methodology is to be able to formulate the dynamics and elasticities of a given variable v_m^i at a given level i with respect to the independent variables that affect it at higher level of the influence diagram. This is all the more true if the variable v_m^i represents capacity, which is the ultimate goal. If the variable v_m^i is a function $v_m^i = \theta(v_n^{i+1}, v_o^{i+1})$ of the variables v_n^{i+1} and v_o^{i+1} , and that the variable v_o^{i+1} is itself a function $v_o^{i+1} = g(v_p^{i+2}, v_q^{i+2})$ of two other variables v_p^{i+2} and v_q^{i+2} , then the functional relationship $v_m^i = \theta(v_n^{i+1}, v_o^{i+1})$ can also be expressed as $v_m^i = \theta(v_n^{i+1}, g(v_p^{i+2}, v_q^{i+2}))$ or $v_m^i = \psi(v_n^{i+1}, v_p^{i+2}, v_q^{i+2})$. The new relationship ψ is a function of function $\theta(g(x))$, also noted $(\theta \circ g)(x)$. The chain rule for differentiation states that, if $\psi(x) = \theta(g(x))$, then $\frac{d\psi(x)}{dx} = \frac{d\theta(g(x))}{d g(x)} \times \frac{d g(x)}{dx}$. The dynamics of the variable v_m^i formulated in Equation 6-13 can therefore be expressed with respect to the three variables v_n^{i+1} , v_p^{i+2} and v_q^{i+2} , as follows:

$$\overline{\delta(v_m^i)} = \overline{\nabla \theta(v_n^{i+1}, g(v_p^{i+2}, v_q^{i+2}))} = \left(\begin{array}{c} \frac{\partial \theta(v_n^{i+1}, g(v_p^{i+2}, v_q^{i+2}))}{\partial v_n^{i+1}} \\ \frac{\partial \theta(v_n^{i+1}, g(v_p^{i+2}, v_q^{i+2}))}{\partial g(v_p^{i+2}, v_q^{i+2})} \times \frac{\partial g(v_p^{i+2}, v_q^{i+2})}{\partial v_p^{i+2}} \\ \frac{\partial \theta(v_n^{i+1}, g(v_p^{i+2}, v_q^{i+2}))}{\partial g(v_p^{i+2}, v_q^{i+2})} \times \frac{\partial g(v_p^{i+2}, v_q^{i+2})}{\partial v_q^{i+2}} \end{array} \right)$$

Equation 6-17

The elasticity of the variable v_m^i with respect to the variable v_n^{i+1} remains unchanged. However, the elasticities of v_m^i with respect to the variable v_o^{i+1} can be expressed in terms of the two variables v_p^{i+2} and v_q^{i+2} as the elasticity of a function of function.

$$\left\{ \begin{array}{l} \varepsilon_{v_m^i}(v_n^{i+1}) = \frac{v_n^{i+1}}{v_m^i} \times \frac{\partial \theta(v_n^{i+1}, g(v_p^{i+2}, v_q^{i+2}))}{\partial v_n^{i+1}} \\ \varepsilon_{v_m^i}(v_p^{i+2}) = \frac{v_p^{i+2}}{v_m^i} \times \frac{\partial \theta(v_n^{i+1}, g(v_p^{i+2}, v_q^{i+2}))}{\partial g(v_p^{i+2}, v_q^{i+2})} \times \frac{\partial g(v_p^{i+2}, v_q^{i+2})}{\partial v_p^{i+2}} \\ \varepsilon_{v_m^i}(v_q^{i+2}) = \frac{v_q^{i+2}}{v_m^i} \times \frac{\partial \theta(v_n^{i+1}, g(v_p^{i+2}, v_q^{i+2}))}{\partial g(v_p^{i+2}, v_q^{i+2})} \times \frac{\partial g(v_p^{i+2}, v_q^{i+2})}{\partial v_q^{i+2}} \end{array} \right.$$

Equation 6-18

Let $\theta(g(x)) = (\theta \circ g)(x)$ be a function of function. Based on the fundamental definition of elasticity, expressed in Equation 6-10, the elasticity $\varepsilon(\theta(g(x)))$ can be formulated as follows:

$$\varepsilon_{\theta(g(x))}(x) = \frac{x}{\theta(g(x))} \times \frac{\partial \theta(g(x))}{\partial g(x)} \times \frac{\partial g(x)}{\partial x}$$

Equation 6-19

If both the numerator and denominator are multiplied by the term $g(x)$, Equation 6-19 can be transformed into

$$\varepsilon_{\theta(g(x))}(x) = \left(\frac{g(x)}{\theta(g(x))} \times \frac{\partial \theta(g(x))}{\partial g(x)} \right) \times \left(\frac{x}{g(x)} \times \frac{\partial g(x)}{\partial x} \right)$$

Equation 6-20

The expression in Equation 6-20 is the product of the elasticity $\varepsilon_{\theta(g(x))}(g(x))$ of the function of function $\theta(g(x))$ with respect to its argument $g(x)$ times the elasticity $\varepsilon_{g(x)}(x)$ of the function $g(x)$ with respect to the variable x . By analogy with the chain rule of differentiation, let us name this latter rule the **chain rule of elasticities**, which is formulated as follows:

if $\psi(x) = \theta(\mathcal{G}(x))$, i.e. $\psi(x) = (\theta \circ \mathcal{G})(x)$,

then $\varepsilon_{\psi(x)}(x) = \varepsilon_{\theta(\mathcal{G}(x))}(\mathcal{G}(x)) \times \varepsilon_{\mathcal{G}(x)}(x)$

Equation 6-21

Based on this rule, the formulation of the elasticities of the variable v_m^i with respect to the three variables v_n^{i+1} , v_p^{i+2} and v_q^{i+2} in Equation 6-18 can be transformed into:

$$\begin{cases} \varepsilon_{v_m^i}(v_n^{i+1}) = \frac{v_n^{i+1}}{v_m^i} \times \frac{\partial \theta(v_n^{i+1}, \mathcal{G}(v_p^{i+2}, v_q^{i+2}))}{\partial v_n^{i+1}} \\ \varepsilon_{v_m^i}(v_p^{i+2}) = \varepsilon_{v_m^i}(v_o^{i+1}) \times \varepsilon_{v_o^{i+1}}(v_p^{i+2}) \\ \varepsilon_{v_m^i}(v_q^{i+2}) = \varepsilon_{v_m^i}(v_o^{i+1}) \times \varepsilon_{v_o^{i+1}}(v_q^{i+2}) \end{cases}$$

Equation 6-22

Formulating capacity dynamics and the various elasticities of capacity based on the influence diagram constitutes an analysis process that starts at the bottom of the tree-graph, i.e. at level $i = 0$ for the variable v_a^0 , and ends as soon as no variable $v_n^i, \dots, v_p^j, \dots, v_q^k$ that affects the bottom variable v_a^0 can be substituted any further. In this case, all the variables $v_n^i, \dots, v_p^j, \dots, v_q^k$ represent leaves on the tree-representation of the influence diagram. These variables are independent and the variable v_a^0 subject to specific investigation can be expressed as a function $v_a^0 = \xi(v_n^i, \dots, v_p^j, \dots, v_q^k)$ of all its independent variables. Finally, the appropriate differentiation and application of Equation 6-4 and Equation 6-10 lead to the dynamics of the variable v_a^0 as well as to the various elasticities of this variable with respect to its various disrupting factors, which is the targeted objective. *Qed*

Finally, it is to be noted that this methodology also enables the image of capacity to be refined. A variable z at one level i is first expressed in terms of a variable y of the level $(i + 1)$ through a functional relationship $\theta(y)$. Let B the domain of the function $\theta(y)$, and C its image, i.e. $\theta: B \rightarrow C: y \rightarrow z = \theta(y)$. At the next iteration, the variable y at the level $(i + 1)$, if it is not independent, can be expressed in terms of a variable x of the level

$(i + 2)$ through a functional relationship $\mathcal{G}(x)$. Let A the domain of the function $\mathcal{G}(x)$ and, obviously, B its image, i.e. $\mathcal{G} : A \rightarrow B : x \rightarrow y = \mathcal{G}(x)$. One knows however that the higher the level of the variable is in the tree-representation of the influence diagram, the more precise the domain and, consequently, the image of the functional relationships. Indeed, in Figure 6-3, the domain of the leaves is relatively well known and depend either on technological or operational constraints. For instance, it is commonly recognised that approach speed varied between 120 Kts and 160 Kts on final approach; one also knows that arrival runway occupancy time (AROT) can vary between 40 and 70 seconds, even 120 seconds when backtrack in operated. Beyond those limits, approach speed and AROT are unlikely or result from unrealistic figures that are statistically non representative. For those independent variables for which the domain cannot be identified based on expertise, measures and statistical analysis results in more accurate domains. In contrast, the domain and image of the root is not known *a priori* and cannot be measured directly. It is relatively difficult to give, prior to any kind of analysis, the range in which capacity can fluctuate. Therefore, substituting a variable at level $i + 1$ by variables from level $(i + 2)$ in order to express a variable at level i enables us to refine the domain and the image of the function $\psi : A \rightarrow C : \psi(x) = \theta(\mathcal{G}(x))$ that links the variable at level i to those at level $(i + 2)$. By analogy to photographic techniques, this methodology for enhancing the image precision is referred to as the **image focus principle** in the rest of this research.

6.3.2 Assumptions

Since it is the purpose of this Chapter to present and synthesize the concepts of capacity dynamics and elasticities as clearly as possible, any issue that could make this understanding more complex without bringing any added value to the description of the concepts should be identified and put aside. In order to achieve this objective, two assumptions are made: first the traffic demand constancy and, second, the fleet homogeneity.

Capacity analyses are usually performed on a predefined traffic sample, which represents either traffic demand or, most often, accommodated traffic. Over a relatively long period of time, it can be assumed that the traffic demand and, therefore, accommodated traffic are statistically representative; their average is relatively constant. Consequently, the average inbound and outbound fleet mixes are relatively constant as well. In order to make the

synthesising of the concepts of capacity dynamics and elasticities as clear as possible, the assumption of **Traffic Demand Constancy** will be made.

The second assumption is related to the heterogeneity of both inbound and outbound traffic. Runways are usually operated to accommodate different types of aircraft. Each type of aircraft has its own performance characteristics, in terms of approach speed, requirements in terms of wake vortex separation minima, and runway occupancy times. For instance, heavy jets approach at much higher speed than light aircraft, because of their greater landing weight and consequently their higher stall speed. Heavy jets also spend more time to brake than light aircraft, and therefore occupy the runway for a longer time. It is also recognised that airborne in-trail spacing is also dependent on sequences of successive aircraft types: the in-trail spacing between a heavy jet and a light aircraft must be minimum 6 NM according to ICAO (1996) whilst this minimum can be reduced to 4 NM if the following aircraft is itself another heavy jet. This heterogeneity pushes airport modellers to disaggregate fleet into aircraft classes. The greater the number of classes, the more complex the calculation, but the greater the accuracy of the results as well. Because the objective of this section is to formulate the concepts of capacity dynamics in as clear as possible way, it will be assumed that all the aircraft types are part of one single class, characterised by the weighted average performance of all its aircraft types. The concepts of capacity dynamics, elasticities and stability will therefore be first formulated independently of aircraft type. This is the **Fleet Homogeneity** assumption.

Like the previous factors of arrival runway occupancy time and time-based airborne in-trail spacing minima, two of these three capacity disrupters are dependent on aircraft type. Distance-based airborne in-trail spacing minima are also dependent on aircraft type because of specific wake vortex.

The two assumptions of traffic demand constancy and fleet homogeneity enables us to simplify the runway capacity influence diagram shown in Figure 6-3. The "light" runway capacity influence diagram is presented in Figure 6-4.

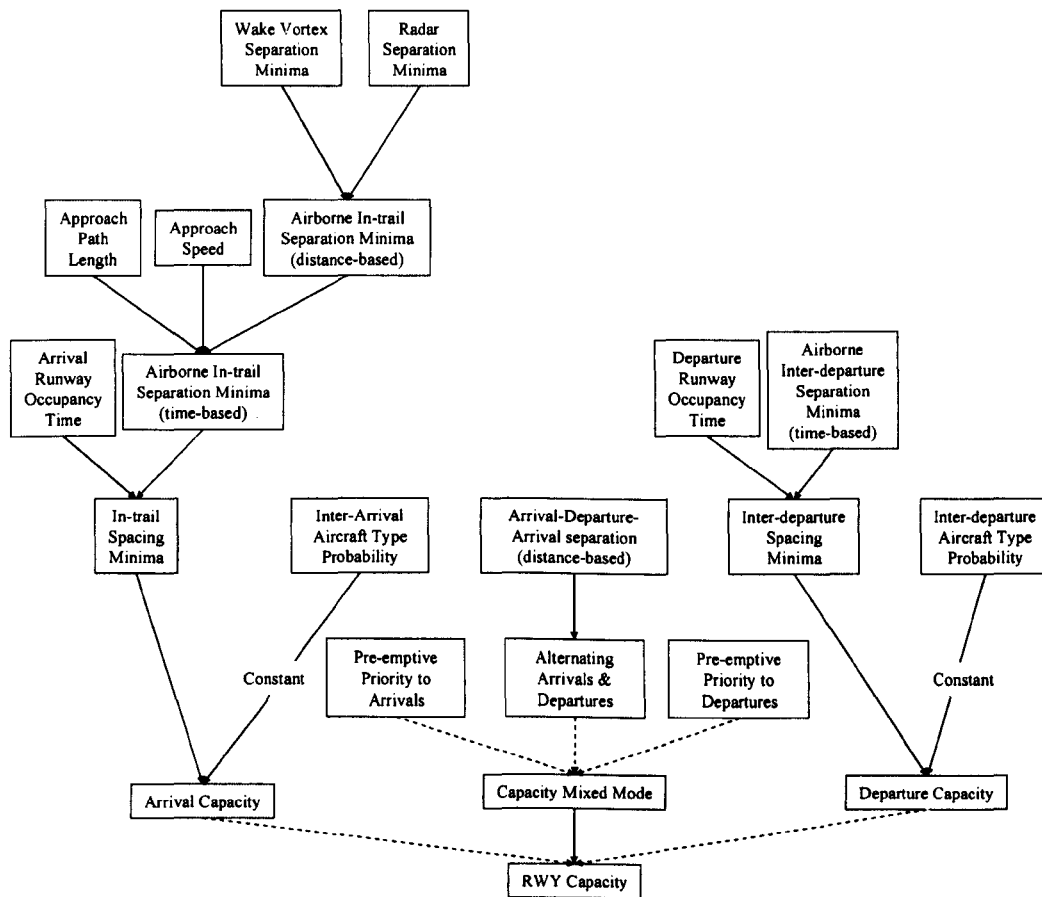


Figure 6-4 – Runway Capacity Influence Hierarchy, based on Traffic Demand Constancy and Homogeneity Fleet Assumptions

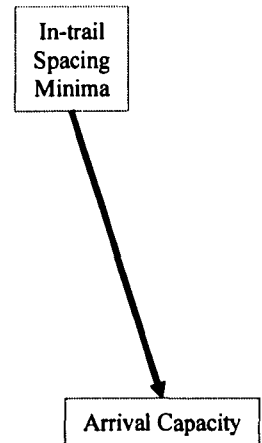
These two assumptions can however be released in further research, in order to be able to draw further conclusions on variable traffic demand, variable traffic mix and heterogeneous fleet. An example is presented in Section 6.4, which addresses heterogeneous fleet mix. But let us first synthesize capacity dynamics and elasticities of capacity with these two assumptions to set up a robust conceptual basis.

As shown in Figure 6-4, runway capacity is composed of three major components: arrival capacity, departure capacity and mixed mode capacity. The first two components of arrival and departure capacity will be analysed in the next Section from a dynamic perspective.

6.3.3 Synthesising Arrival Capacity Dynamics and Elasticities

6.3.3.1 Impact of Inter-arrival Spacing

Consider first the dynamics and elasticities of arrival capacity. The very first level above arrival capacity in the influence diagram represented in Figure 6-4 is the inter-arrival spacing. From the general concept of capacity described in Section 4.2, arrival capacity is the reciprocal of the arithmetic mean of the time intervals between successive arrivals. Based on Equation 4-12, the arrival capacity is the inverse of the weighted average inter-arrival spacing. Because of the assumption on fleet homogeneity, one can state that the arrival capacity γ_a is the inverse of the inter-arrival spacing τ_{aa} .



Any real number that is positive and not null can be assigned to in-trail spacing. Indeed, the elapsed time between successive landings can be neither negative nor null, in which case the fundamental rule of single runway occupancy expressed in Section 4.1 would be violated. The domain of the functional relationship leading to capacity is therefore the set of positive and non null real numbers, noted \mathfrak{R}_0^+ . Because the inverse of a positive non null real number is another positive non null real number, the image of this functional relationship is the same set \mathfrak{R}_0^+ . Whilst referring to the *image focus principle* expressed in Section 6.3.1, it is to be noted that both the domain and image of the functional relationship between in-trail spacing and capacity is relatively vague at this stage of the analysis of the influence diagram. It will however be refined step-by-step with the bottom-up analysis of the influence diagram.

The functional relationship between in-trail spacing and capacity can therefore be summarised as follows:

$$\gamma_a(\tau_{aa}) : \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^+ : \tau_{aa} \rightarrow \gamma_a(\tau_{aa}) = \frac{1}{\tau_{aa}}$$

Equation 6-23

In this relationship, capacity tends towards infinite values when in-trail spacing tends towards infinitesimal numbers, whilst capacity tends to zero for large values of in-trail spacing. The function formulated in Equation 6-23 has therefore two asymptotes: one vertical one that is expressed by $\lim_{\tau_{aa} \rightarrow 0} \gamma_a(\tau_{aa}) = \infty$, and a second one that is horizontal and defined by $\lim_{\tau_{aa} \rightarrow \infty} \gamma_a(\tau_{aa}) = 0$, as represented in Figure 6-5. The arrival capacity function is a rectangular hyperbola.

As defined in Sections 6.2.2 and 6.2.4, the two concepts of capacity dynamics and elasticity of capacity are based on differentiation of the capacity function. The differentiation of Equation 6-23 results in

$$\frac{d\gamma_a(\tau_{aa})}{d\tau_{aa}} = -\frac{1}{\tau_{aa}^2}$$

Equation 6-24

The image of the first-order differentiation of capacity is the set of negative and non null real numbers, noted \mathfrak{R}_0^- . This differentiation also includes two asymptotes: one vertical one

expressed by $\lim_{\tau_{aa} \rightarrow 0} \frac{d\gamma_a(\tau_{aa})}{d\tau_{aa}} = -\infty$, and a second one that is horizontal and defined as

$\lim_{\tau_{aa} \rightarrow \infty} \frac{d\gamma_a(\tau_{aa})}{d\tau_{aa}} = 0$. Based on Equation 6-5 and Equation 6-24, the arrival capacity dynamics

δ_{γ_a} with respect to in-trail spacing τ_{aa} is formulated as follows:

$$\delta_{\gamma_a} : \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^- : \tau_{aa} \rightarrow \delta_{\gamma_a} = -\frac{1}{\tau_{aa}^2}$$

Equation 6-25

Like arrival capacity, the arrival capacity dynamics with respect to in-trail spacing τ_{aa} is represented in Figure 6-5. Capacity dynamics is also a rectangular hyperbola, but negative.

Arrival capacity dynamics provides the instantaneous rate of capacity change with respect to in-trail spacing, which is a performance indication of how quickly arrival capacity is able to change further to some fluctuation of in-trail spacing, in the vicinity of a specific value of that factor. For instance, 80" in-trail spacing results in 45 arrivals/hour. Any marginal change of in-trail spacing by 1" in the vicinity of 80" leads to a capacity fluctuation of -0.56 arrivals/hour/sec.

As can be seen in Equation 6-25, any division of in-trail spacing by a factor of 2 multiplies arrival capacity dynamics by a factor 4. In other words, **any division of in-trail spacing by a factor of 2 multiplies the magnitude of the impact on capacity change by a factor of 4, for the same marginal fluctuation of in-trail spacing.** And vice-versa, doubling in-trail spacing leads to a magnitude of potential change of capacity divided by 4. This means that 1"-marginal fluctuation of in-trail spacing will have 4 times more impact on capacity at 40" than at 80". Indeed, any marginal change of in-trail spacing by 1" in the vicinity of 40" leads to a capacity fluctuation of -2.25 arrivals/hour, instead of -0.56 arrivals/hour for 80" in-trail spacing. Paradoxically, capacity is doubled, but capacity stability is decreased by a factor 4. Capacity stability and robustness will be investigated later in Section 6.5.

The inter-arrival spacing elasticity of capacity, noted $\varepsilon_{\gamma_a}(\tau_{aa})$, is the ratio of the percentage change of capacity with respect to percentage fluctuation of in-trail spacing. The instantiation of Equation 6-9 with the function expressed in Equation 6-23 and related differentiation in Equation 6-24 results in the formulation of the inter-arrival spacing elasticity of capacity, as follows:

$$\varepsilon_{\gamma_a}(\tau_{aa}) : \mathfrak{R}_0^+ \rightarrow [-1] : \varepsilon_{\gamma_a}(\tau_{aa}) = -1$$

Equation 6-26

because
$$\frac{\tau_{aa} \times \left(-\frac{1}{\tau_{aa}^2} \right)}{\frac{1}{\tau_{aa}}} = -1.$$

It can be concluded that the percentage change in arrival capacity is equal to the negative percentage change in in-trail separation. In other words, **any percent increase (decrease) of in-trail spacing has an impact on arrival capacity equal to a one percent decrease**

(increase). The in-trail spacing elasticity of capacity can therefore be qualified as being **negatively unitary elastic**: it is unitary elastic because $\left| \varepsilon_{\gamma_a}(\tau_{aa}) \right| = 1$, but negatively as arrival capacity changes inversely with respect to in-trail spacing.

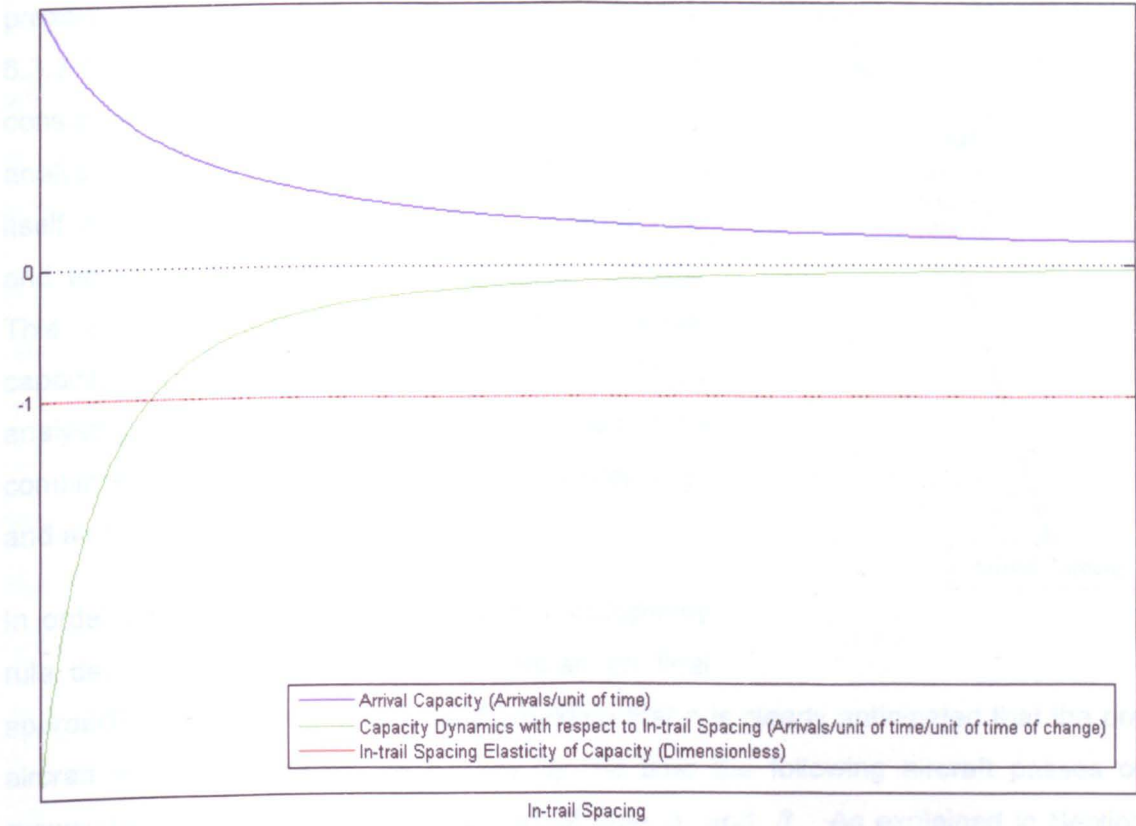
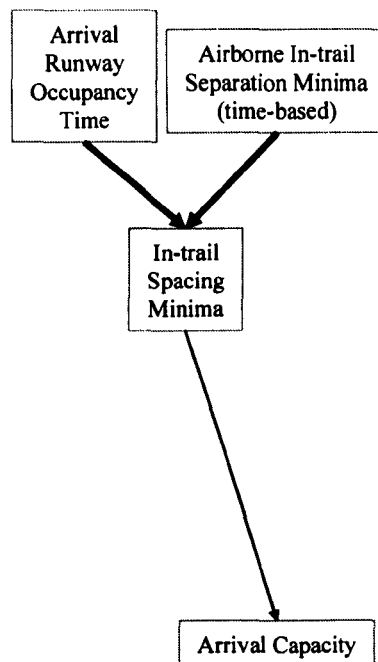


Figure 6-5 – Impact of Weighted Average In-trail Spacing on Capacity

6.3.3.2 Related Impact of Arrival Runway Occupancy Time and Airborne In-trail Separation Minima

As described in Section 6.3.1, the methodology used to formulate capacity dynamics and the various elasticities of capacity is based on the bottom-up analysis of the influence diagram, presented in Figure 6-4. In the previous Section 6.3.3.1, the very first level above arrival capacity was considered, and the impact of in-trail spacing was analysed. It is known however that in-trail spacing is itself dependent on arrival runway occupancy time and time-based airborne in-trail separation minima. This Section tackles the formulation of arrival capacity dynamics and elasticities of capacity by analysing the second level, which is the impact of the combined effect of arrival runway occupancy time and airborne in-trail spacing minima.



In order not to violate the single runway occupancy rule described in Section 4.1, any aircraft on final approach may be committed to land providing that it is clearly anticipated that the preceding aircraft will have vacated the runway by the time the following aircraft passes over the runway threshold. Consider two aircraft of type α and β . As explained in Section 4.3.1, the single runway occupancy rule means that the time interval $\tau_{\alpha\beta}$ between two successive approaches α and β must be greater or equal to the maximum between the airborne in-trail spacing minima driven by radar technology and aerodynamics, noted $\tau_{\alpha\beta}^{air}$, and the runway occupancy time (AROT) of the preceding aircraft α , noted τ_{α}^{arot} , i.e.

$$\tau_{\alpha\beta} = \max(\tau_{\alpha}^{arot}; \tau_{\alpha\beta}^{air})$$

Equation 6-27

In Equation 6-27, both the runway occupancy time and the airborne in-trail spacing are time based.

Based on the simplification related to the fleet homogeneity assumption, Equation 6-27 becomes

$$\tau_{aa} = \max(\tau^{arot}; \tau_{aa}^{air})$$

Equation 6-28

in which τ^{arot} can be considered as the weighted average of the runway occupancy time of the various types of aircraft whilst τ_{aa}^{air} is the weighted average of the airborne in-trail spacing minima for all the possible combinations of approach sequences between successive aircraft types.

Both runway occupancy time and airborne in-trail spacing minima can theoretically be assigned any positive and non null real number. As the maximum of two positive and non null real numbers is a positive and non null real number, the domain \mathfrak{R}_0^+ of the functional relationship between capacity and in-trail spacing remains unchanged. Consequently, the image \mathfrak{R}_0^+ of this function remains unchanged as well. As explained in Section 6.3.3.1, both the domain and image will be refined through the image focus principle described in Section 6.3.1, during the top-down analysis of the capacity influence diagram.

The functional relationship between in-trail spacing and capacity expressed in Equation 6-23 can be reformulated as a function of both runway occupancy and airborne in-trail spacing, as follows:

$$\gamma_a(\tau^{arot}, \tau_{aa}^{air}): \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^+ : (\tau^{arot}, \tau_{aa}^{air}) \rightarrow \gamma_a(\tau^{arot}, \tau_{aa}^{air}) = \begin{cases} \frac{1}{\tau^{arot}}, & \text{if } (\tau^{arot} \geq \tau_{aa}^{air}) \\ \frac{1}{\tau_{aa}^{air}}, & \text{if } (\tau^{arot} < \tau_{aa}^{air}) \end{cases}$$

Equation 6-29

or, yet,

$$\gamma_a(\tau^{arot}, \tau_{aa}^{air}) = \min\left(\frac{1}{\tau^{arot}}; \frac{1}{\tau_{aa}^{air}}\right)$$

Equation 6-30

The functional relationship between capacity, runway occupancy time and airborne in-trail spacing represents a 3-dimensional hyperbolic surface, which is displayed in Figure 6-6 under two different views in order to facilitate the visualisation. This surface tends to infinity for null values of both arrival runway occupancy time and airborne in-trail spacing, and tends to zero for infinite values of one of these two factors. The surface is discontinuous when arrival occupancy time equals the airborne in-trail spacing, represented by the red bold curve in Figure 6-6. This inflexion curve shows clearly that **any decrease of arrival runway occupancy below the level of airborne in-trail spacing minima does not impact at all on capacity**; and vice versa, neither shall any decrease of airborne in-trail spacing below the level of arrival runway occupancy.

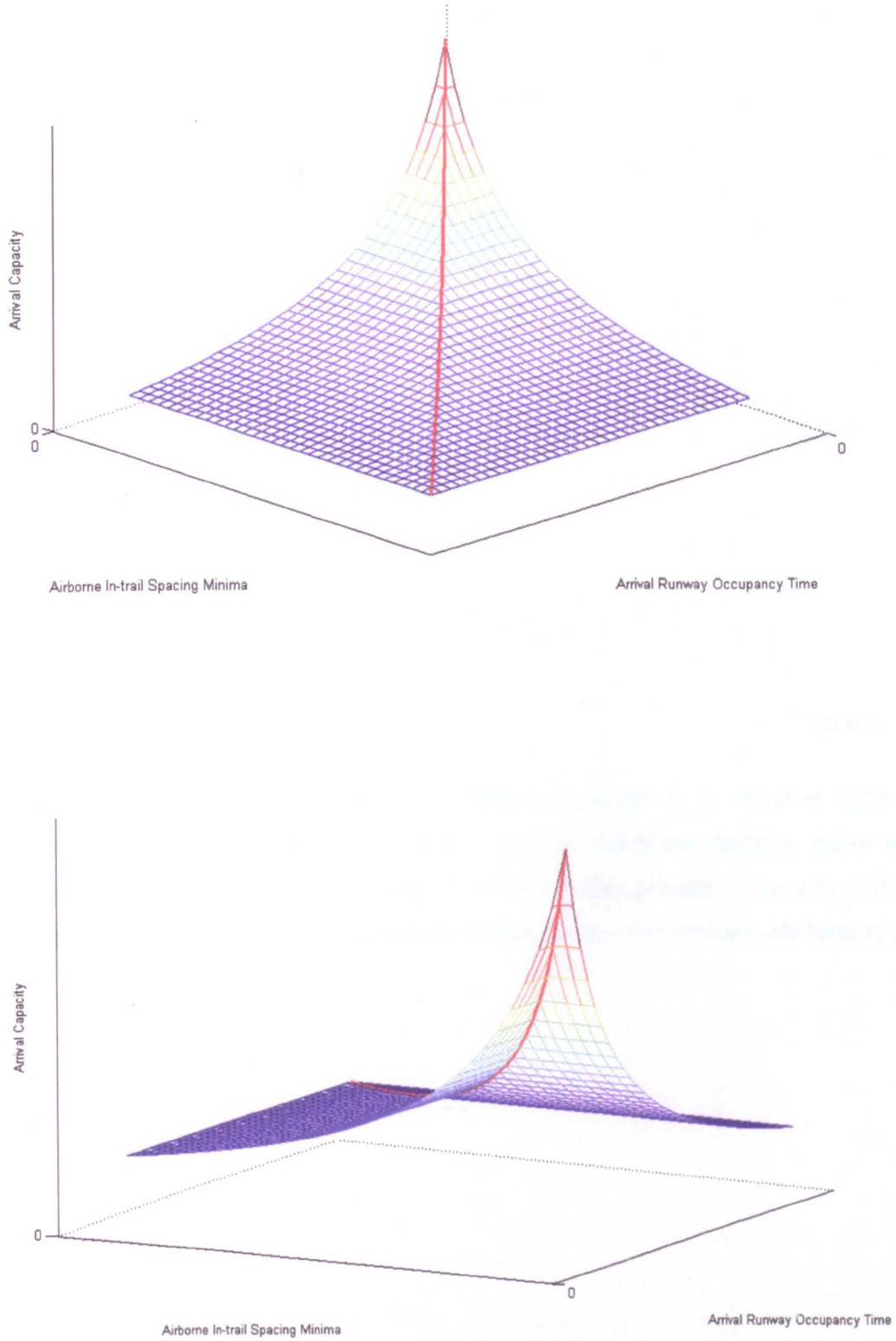


Figure 6-6 – Combined Impact of AROT and In-trail Spacing on Capacity

The arrival capacity dynamics with respect to arrival runway occupancy time and airborne in-trail spacing minima is the vector composed of the differential derivatives of arrival capacity with respect to these two factors. Based on the general formulation of capacity dynamics expressed in Equation 6-5, the arrival capacity dynamics with respect to arrival runway occupancy time and airborne in-trail spacing minima is synthesized as follows:

$$\overline{\delta_{\gamma_a}(\tau^{arot}, \tau^{air})}: \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^- : (\tau^{arot}, \tau^{air}) \rightarrow \overline{\delta_{\gamma_a}(\tau^{arot}, \tau^{air})} = \begin{cases} \left(\frac{-1}{(\tau^{arot})^2}; 0 \right), \forall \tau^{arot} \geq \tau^{air} \\ \left(0; \frac{-1}{(\tau^{air})^2} \right), \forall \tau^{arot} < \tau^{air} \end{cases}$$

Equation 6-31

and yet, the magnitude of capacity dynamics is

$$\left\| \overline{\delta_{\gamma_a}(\tau^{arot}, \tau^{air})} \right\| = \max \left(\frac{1}{(\tau^{arot})^2}; \frac{1}{(\tau^{air})^2} \right)$$

Equation 6-32

As shown in Figure 6-7, the arrival capacity dynamics function is a negative hyperbolic surface that tends to zero with an infinite value of one of these two factors, either arrival runway occupancy or airborne in-trail spacing, whichever is the greater. Capacity dynamics also tends towards negative infinite values when the two factors simultaneously tend to zero.

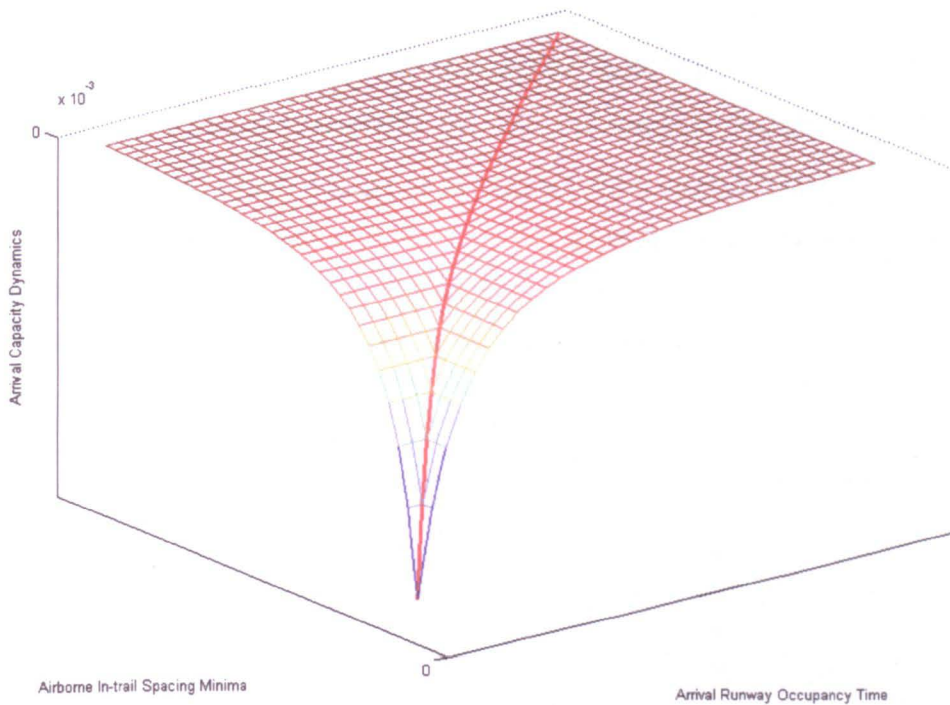


Figure 6-7 – Arrival Capacity Dynamics w.r.t. AROT and Airborne In-trail Spacing Minima

In order to fully understand the combined impact of AROT and airborne in-trail spacing minima, the gradient representation of capacity dynamics with respect to these two factors is shown in Figure 6-8. In this figure, the various lines, broken with a 90° angle, represent *capacity isobars*. Any couple $(\tau^{arot}, \tau_{aa}^{air})$ on one of these isobars leads to the same capacity of that isobar. The arrows represent the direction in which capacity changes most quickly, and the length of the arrows represents the magnitude or intensity of capacity change.

Figure 6-8 includes a collection of vectors (arrows) pointing into the direction of increasing capacity for marginal fluctuation of both AROT and airborne in-trail spacing. The more AROT and airborne in-trail spacing decrease, the more quickly capacity changes. It was concluded in Section 6.3.3.1 that any division of in-trail spacing by a factor of 2 multiplies arrival capacity by a factor of 4, and vice versa. When in-trail spacing is dependent on AROT and airborne in-trail spacing, this rule is still valid providing that one factor does not take over the other one. As represented in Figure 6-8, and according to Equation 6-32, capacity increases in a quadratic way with respect to any decrease of the predominant factor between AROT and airborne in-trail spacing minima, up to the **AROT-Airborne Spacing**

Equity line at which the two factors are equal. This limit is represented by the bold red diagonal in Figure 6-8. On the right hand side of this line, AROT is greater than airborne in-trail spacing and arrival capacity dynamics is dependent on AROT only, as reported in Equation 6-29. The second element of the capacity dynamics vector formulated in Equation 6-31 is null $\forall \tau^{arot} \geq \tau_{aa}^{air}$, which confirms the fact that capacity remains constant despite in-trail spacing fluctuation when this latter is smaller than AROT. Capacity increases in a quadratic way with any decrease of AROT, up to reaching the equity line. Beyond this line, any further AROT decrease has no further impact on capacity, and any capacity increase turns into the direction of airborne in-trail spacing decrease.

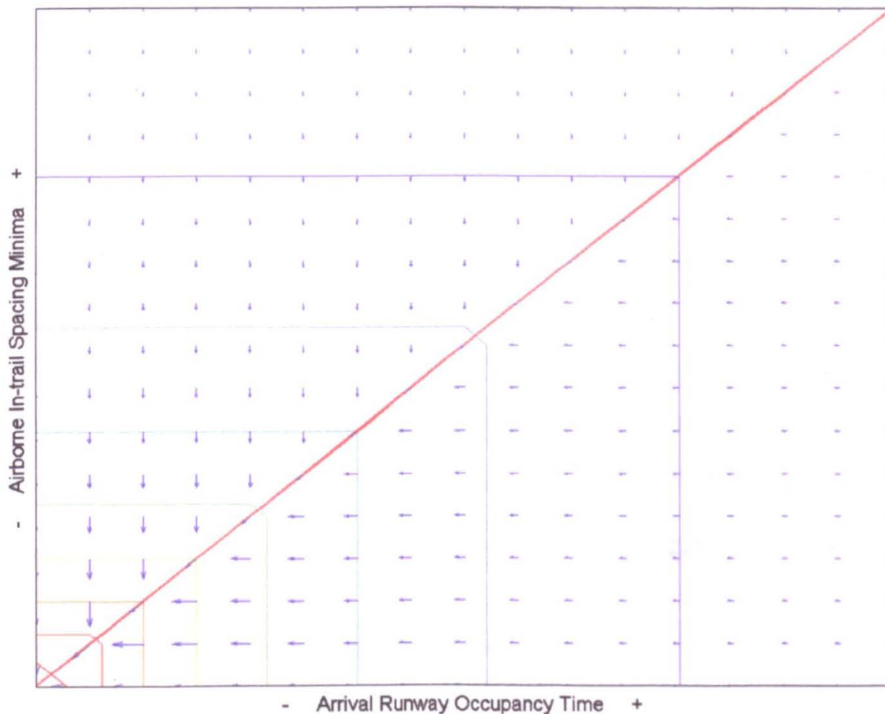


Figure 6-8 – Gradient Representation of Arrival Capacity Dynamics w.r.t. AROT and Airborne In-trail Spacing Minima

So, as formulated in Equation 6-31 and illustrated in Figure 6-8, any decrease of arrival runway occupancy below the level of airborne in-trail spacing minima does not contribute to capacity enhancement; and vice versa. Consequently, it is obvious that any investment in new runway exits becomes useless as soon as the runway occupancy time related to the use of this new runway exit is below the airborne in-trail spacing. Too often, this conclusion from the combined impact of AROT and airborne spacing is not sufficiently considered.

The AROT-elasticity of capacity, noted $\varepsilon_{\gamma_a}(\tau^{arot})$, is the ratio of the percentage change of capacity with respect to percentage fluctuation of arrival runway occupancy time. By applying the basic Equation 6-10 of elasticity whilst referring to Equation 6-29 and Equation 6-31, the AROT-elasticity of capacity can be synthesized as follows:

$$\varepsilon_{\gamma_a}(\tau^{arot}) = \begin{cases} \frac{\tau^{arot}}{1/\tau^{arot}} \times \frac{-1}{(\tau^{arot})^2}, \forall \tau^{arot} \geq \tau_{aa}^{air} \\ 0, \forall \tau^{arot} < \tau_{aa}^{air} \end{cases}$$

or yet,

$$\varepsilon_{\gamma_a}(\tau^{arot}) = \begin{cases} -1, \forall \tau^{arot} \geq \tau_{aa}^{air} \\ 0, \forall \tau^{arot} < \tau_{aa}^{air} \end{cases}$$

Equation 6-33

It can be concluded that the percentage change in arrival capacity is equal to the negative percentage change in arrival runway occupancy when this latter is greater than airborne in-trail spacing. However, arrival runway occupancy time has absolutely no impact on capacity when it is smaller than airborne spacing. In other words, the AROT-elasticity of capacity is **negatively unitary elastic** (i.e. $\varepsilon_{\gamma_a}(\tau^{arot}) = -1$) when AROT is greater than airborne spacing, and is **perfectly inelastic** ($\varepsilon_{\gamma_a}(\tau^{arot}) = 0$) when AROT is smaller than airborne spacing.

In a similar way, the elasticity of capacity with respect to airborne in-trail spacing minima, noted $\varepsilon_{\gamma_a}(\tau_{aa}^{air})$ is formulated as follows:

$$\varepsilon_{\gamma_a}(\tau_{aa}^{air}) = \begin{cases} 0, \forall \tau_{aa}^{air} \leq \tau^{arot} \\ -1, \forall \tau_{aa}^{air} > \tau^{arot} \end{cases}$$

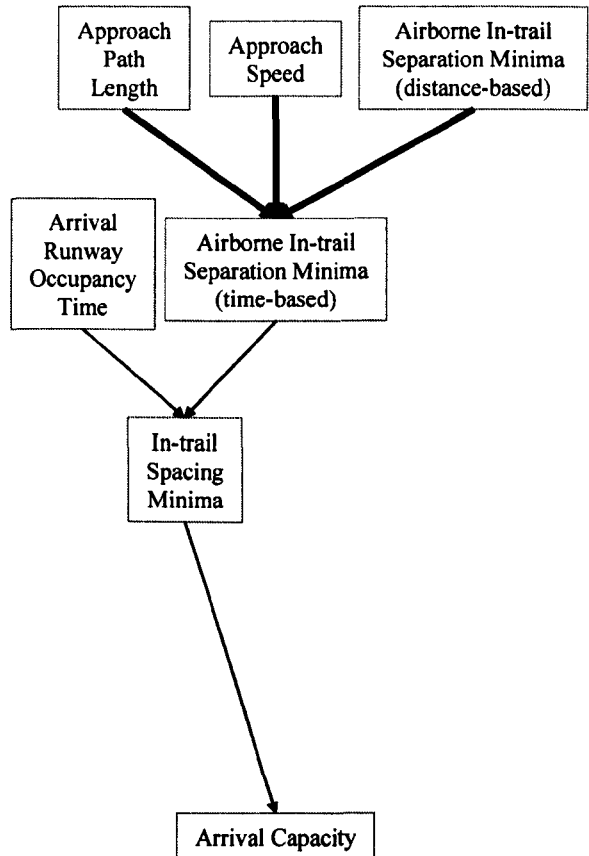
Equation 6-34

This leads to a similar conclusion, that the capacity is **negatively unitary elastic** with respect to airborne in-trail spacing (i.e. $\varepsilon_{\gamma_a}(\tau_{aa}^{air}) = -1$) when airborne spacing is predominant

compared to AROT; it is however **perfectly inelastic** ($\varepsilon_{\gamma_a}(\tau_{aa}^{air}) = 0$) when AROT is greater than airborne spacing.

6.3.3.3 Related Impact of Approach Speed and Distance-based Airborne Separation Minima

Based on the capacity influence diagram presented in Figure 6-4, the impact of inter-arrival spacing is analysed in Section 6.3.3.1, whilst Section 6.3.3.2 addresses the related effect of arrival runway occupancy time and airborne in-trail separation minima. It was explained in Section 4.3.1 how airborne in-trail separation minima, which are time-based, are dependent on the three following variables: the approach speed, the distance-based airborne separation minima, and the length of the common final approach path. This latter parameter is fixed by terminal manoeuvring area (TMA) design and technology (type of instrument landing systems – ILS, MLS, ...). Hence its name that includes the term 'common'.



Equation 4-19 formulates the functional relationship between arrival capacity and these three variables. In this equation, it is to be noticed that the length of common final approach path appears only in the opening case, when there exists some speed differential between successive approaches. However, like in the previous Sections, the capacity dynamics and elasticities are formulated independently of aircraft type, based on the fleet homogeneity assumption.

As per Equation 4-19, and whilst taking the fleet homogeneity assumption into consideration, the time-based airborne separation minima τ_{aa}^{air} between successive arrivals is formulated as follows:

$$\tau_{aa}^{air} = \frac{\delta_{aa}^{air}}{v}$$

Equation 6-35

where δ_{aa}^{air} represents the distance-based in-trail spacing minima and v the approach speed. Because of the fleet homogeneity assumption, the time-based airborne separation minima become independent on the length of common final approach path. This latter parameter will therefore be ignored in the rest of this development.

The functional relationship that links arrival capacity to both arrival runway occupancy and time-based airborne in-trail spacing, expressed in Equation 6-29, can be reformulated as a function of the three factors runway occupancy, distance-based airborne in-trail spacing, and final approach speed. This extended capacity relationship is synthesized as follows:

$$\begin{aligned} &\gamma_a(\tau^{arot}, \delta_{aa}^{air}, v): \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^+ : \\ &(\tau^{arot}, \delta_{aa}^{air}, v) \rightarrow \gamma_a(\tau^{arot}, \delta_{aa}^{air}, v) = \begin{cases} \frac{1}{\tau^{arot}}, & \text{if } \left(\tau^{arot} \geq \frac{v}{\delta_{aa}^{air}} \right) \\ \frac{v}{\delta_{aa}^{air}}, & \text{if } \left(\tau^{arot} < \frac{v}{\delta_{aa}^{air}} \right) \end{cases} \end{aligned}$$

Equation 6-36

The differentiation of the time-based in-trail spacing with respect to distance-based in-trail spacing and final approach speed is

$$\nabla \tau_{aa}^{air}(\delta_{aa}^{air}, v) = \left(\frac{1}{v}, -\frac{\delta_{aa}^{air}}{v^2} \right)$$

Equation 6-37

Based on the general formulation of capacity dynamics expressed in Equation 6-5 and the chain rule of differentiation, the arrival capacity dynamics with respect to arrival runway

occupancy time, distance-based airborne in-trail spacing minima and final approach speed is synthesized as follows:

$$\overline{\delta_{\gamma_a}(\tau^{arot}, \delta_{aa}^{air}, v)}: \mathcal{R}_0^+ \times \mathcal{R}_0^+ \times \mathcal{R}_0^+ \rightarrow \mathcal{R}_0^- :$$

$$\left(\tau^{arot}, \delta_{aa}^{air}, v \right) \rightarrow \overline{\delta_{\gamma_a}(\tau^{arot}, \delta_{aa}^{air}, v)} \begin{cases} \left(\frac{-1}{(\tau^{arot})^2}; 0; 0 \right), \forall \tau^{arot} \geq \frac{v}{\delta_{aa}^{air}} \\ \left(0; \frac{-v}{\delta_{aa}^{air^2}}; \frac{1}{\delta_{aa}^{air}} \right), \forall \tau^{arot} < \frac{v}{\delta_{aa}^{air}} \end{cases}$$

Equation 6-38

The elasticity of capacity with respect to distance-based airborne in-trail spacing minima, noted $\varepsilon_{\gamma_a}(\delta_{aa}^{air})$ can be calculated by using the chain rule of elasticities, as follows:

$$\varepsilon_{\gamma_a}(\delta_{aa}^{air}) = \varepsilon_{\gamma_a}(\tau_{aa}^{air}) \times \varepsilon_{\tau_{aa}^{air}}(\delta_{aa}^{air})$$

It can be calculated that

$$\varepsilon_{\tau_{aa}^{air}}(\delta_{aa}^{air}) = 1$$

therefore,

$$\varepsilon_{\gamma_a}(\delta_{aa}^{air}) = \begin{cases} 0, \forall \tau^{arot} \geq \frac{v}{\delta_{aa}^{air}} \\ -1, \forall \tau^{arot} < \frac{v}{\delta_{aa}^{air}} \end{cases}$$

Equation 6-39

By using the chain rule of elasticities, the elasticity of arrival capacity with respect to final approach speed can be calculated, in a similar way, as

$$\varepsilon_{\gamma_a}(v) = \begin{cases} 0, \forall \tau^{arot} \geq \frac{v}{\delta_{aa}^{air}} \\ 1, \forall \tau^{arot} < \frac{v}{\delta_{aa}^{air}} \end{cases}$$

Equation 6-40

Equation 6-39 and Equation 6-40 show that arrival capacity is perfectly inelastic with respect to both distance-based in-trail spacing minima and final approach speed when arrival runway occupancy is predominant compared to time-based in-trail spacing minima. However, when time-based in-trail spacing is greater than arrival runway occupancy, arrival capacity is negatively unitary elastic with respect to distance-based in-trail spacing minima and positively unitary elastic with respect to final approach speed. This means that, if time-based in-trail spacing is greater than arrival runway occupancy, any marginal increase of distance-based in-trail spacing minima by 1% leads to a decrease of arrival capacity by 1%, whilst any increase in final approach speed by 1% results in a 1%-increase of arrival capacity.

6.3.3.4 Related Impact of Wake Vortex and Radar Separation Minima

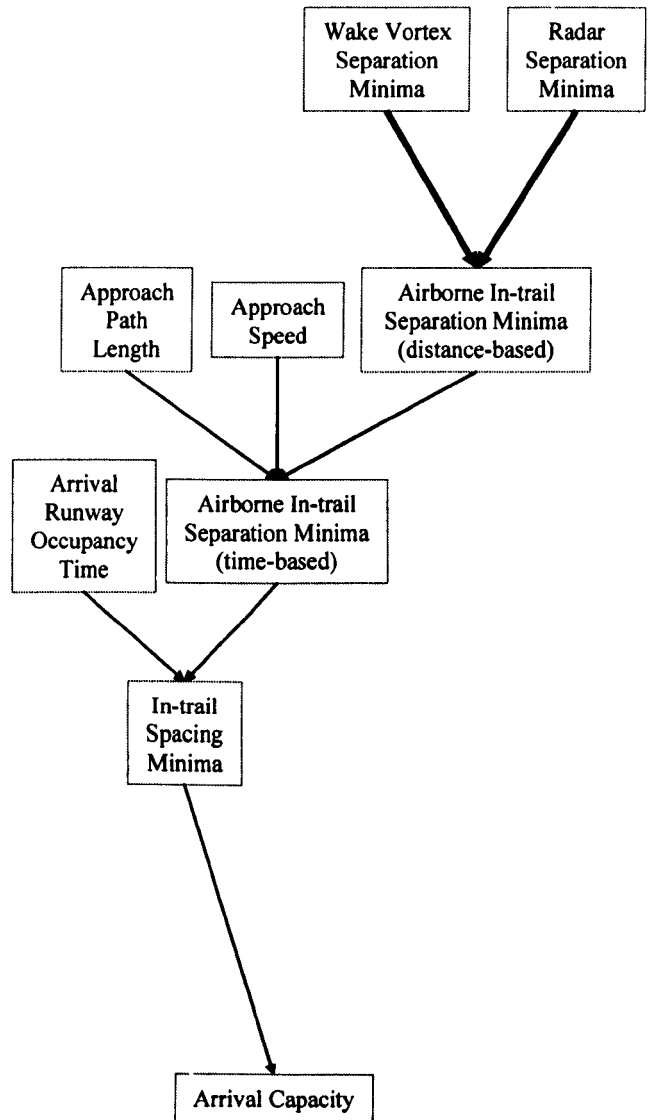
The final level of the runway capacity influence diagram presented in Figure 6-4 addresses the inter-dependent impact of wake vortex and radar separation minima. As explained in Section 4.3.1, the distance-based airborne separation minima between successive approaches under IFR conditions is driven by the predominant factor between radar provision and wake vortex constraints. With the fleet homogeneity assumption, Equation 4-15 can be simplified as follows:

$$\delta_{aa}^{air} = \max(\delta_{aa}^{wv}; \delta^{radar})$$

Equation 6-41

where δ_{aa}^{wv} represents the weighted average of the wake vortex separation minima.

The functional relationship that links arrival capacity to the three factors of runway occupancy, distance-based airborne in-trail spacing, and final approach speed, as expressed in Equation 6-36, can be reformulated as a function of the four factors of runway occupancy, distance-based wake vortex separation minima, radar separation, and final approach speed. Equation 6-36 can therefore be re-synthesized as follows:



$$\gamma_a(\tau^{arot}, \delta_{aa}^{wv}, \delta^{radar}, v): \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^+ :$$

$$(\tau^{arot}, \delta_{aa}^{wv}, \delta^{radar}, v) \rightarrow \gamma_a(\tau^{arot}, \delta_{aa}^{wv}, \delta^{radar}, v) = \begin{cases} \frac{1}{\tau^{arot}}, \text{if} \left(\tau^{arot} \geq \frac{v}{\max(\delta_{aa}^{wv}; \delta^{radar})} \right) \\ \frac{v}{\delta_{aa}^{wv}}, \text{if} \left(\tau^{arot} < \frac{v}{\delta_{aa}^{wv}} \right) \& (\delta_{aa}^{wv} \geq \delta^{radar}) \\ \frac{v}{\delta^{radar}}, \text{if} \left(\tau^{arot} < \frac{v}{\delta^{radar}} \right) \& (\delta_{aa}^{wv} < \delta^{radar}) \end{cases}$$

Equation 6-42

where & represents the Boolean operator AND.

Based again on the chain rule of differentiation, the arrival capacity dynamics with respect to runway occupancy, distance-based wake vortex separation minima, radar separation, and final approach speed can be reformulated as follows:

$$\overline{\delta_{\gamma_a}(\tau^{arot}, \delta_{aa}^{wv}, \delta^{radar}, v)}: \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^- :$$

$$(\tau^{arot}, \delta_{aa}^{wv}, \delta^{radar}, v) \rightarrow \overline{\delta_{\gamma_a}(\tau^{arot}, \delta_{aa}^{wv}, \delta^{radar}, v)} = \begin{cases} \left(\frac{-1}{(\tau^{arot})^2}; 0; 0; 0 \right), \forall \tau^{arot}, \delta_{aa}^{wv}, \delta^{radar} : \left(\tau^{arot} \geq \frac{v}{\max(\delta_{aa}^{wv}; \delta^{radar})} \right) \\ \left(0; \frac{-v}{\delta_{aa}^{wv2}}; 0; \frac{1}{\delta_{aa}^{wv}} \right), \forall \tau^{arot}, \delta_{aa}^{wv}, \delta^{radar} : \left(\left(\tau^{arot} < \frac{v}{\delta_{aa}^{wv}} \right) \& (\delta_{aa}^{wv} \geq \delta^{radar}) \right) \\ \left(0; 0; \frac{-v}{\delta^{radar2}}; \frac{1}{\delta^{radar}} \right), \forall \tau^{arot}, \delta_{aa}^{wv}, \delta^{radar} : \left(\left(\tau^{arot} < \frac{v}{\delta_{aa}^{wv}} \right) \& (\delta_{aa}^{wv} < \delta^{radar}) \right) \end{cases}$$

Equation 6-43

According to the chain rule of elasticities, the wake-vortex elasticity of arrival capacity equals the time-based airborne in-trail spacing elasticity of arrival capacity times the wake-vortex elasticity of time-based airborne in-trail spacing:

$$\varepsilon_{\gamma_a}(\delta_{aa}^{wv}) = \varepsilon_{\gamma_a}(\delta_{aa}^{air}) \times \varepsilon_{\delta_{aa}^{air}}(\delta_{aa}^{wv})$$

The time-based airborne in-trail spacing elasticity of arrival capacity is formulated in Equation 6-39, whilst the wake-vortex elasticity of time-based airborne in-trail spacing is defined by:

$$\varepsilon_{\delta_{aa}^{ar}}(\delta_{aa}^{wv}) = \begin{cases} 1, \forall \delta_{aa}^{wv}, \delta^{radar} : (\delta_{aa}^{wv} \geq \delta^{radar}) \\ 0, \forall \delta_{aa}^{wv}, \delta^{radar} : (\delta_{aa}^{wv} < \delta^{radar}) \end{cases}$$

Therefore, the wake-vortex elasticity of arrival capacity is synthesized as follows:

$$\varepsilon_{\gamma_a}(\delta_{aa}^{wv}) = \begin{cases} 0, \forall \tau^{arot}, \delta_{aa}^{wv}, \delta^{radar} : \left(\left(\tau^{arot} \geq \frac{v}{\max(\delta_{aa}^{wv}; \delta^{radar})} \right) \parallel (\delta_{aa}^{wv} < \delta^{radar}) \right) \\ -1, \forall \tau^{arot}, \delta_{aa}^{wv}, \delta^{radar} : \left(\left(\tau^{arot} < \frac{v}{\max(\delta_{aa}^{wv}; \delta^{radar})} \right) \& (\delta_{aa}^{wv} \geq \delta^{radar}) \right) \end{cases}$$

Equation 6-44

where \parallel represents the Boolean operator OR.

Whilst using a similar approach to formulation deduction, the elasticity of arrival capacity with respect to radar separation can be synthesized as follows:

$$\varepsilon_{\gamma_a}(\delta^{radar}) = \begin{cases} 0, \forall \tau^{arot}, \delta_{aa}^{wv}, \delta^{radar} : \left(\left(\tau^{arot} \geq \frac{v}{\max(\delta_{aa}^{wv}; \delta^{radar})} \right) \parallel (\delta_{aa}^{wv} > \delta^{radar}) \right) \\ -1, \forall \tau^{arot}, \delta_{aa}^{wv}, \delta^{radar} : \left(\left(\tau^{arot} < \frac{v}{\max(\delta_{aa}^{wv}; \delta^{radar})} \right) \& (\delta_{aa}^{wv} \leq \delta^{radar}) \right) \end{cases}$$

Equation 6-45

Based on Equation 6-44, it can be concluded that arrival capacity is negatively unitary elastic with respect to wake vortex separation minima only when this latter factor is predominant compared to radar separation and arrival runway occupancy time. In any other case, wake vortex does not affect arrival capacity. It is however to be recognised that, from an operational perspective, and especially for those runways accommodating heavy jets, wake vortex is most of the time, determinant in the arrival capacity equation. As it will be shown in Section 7.1.3, this can be justified by the fact that heavy jets require between 4 to 6 NM in-trail spacing, i.e. between 70 and 100 seconds separation, what is usually greater than radar separation and runway occupancy time.

Similar conclusions follow from Equation 6-45, that arrival capacity is negatively unitary elastic with respect to radar separation minima only when this latter factor is predominant compared to wake vortex separation and arrival runway occupancy time. This happens at most airports which are not equipped with on-site radar, what generally results in in-trail separation minima greater or equal to 5 NM. In any other case, radar does not affect arrival capacity, what is shown as the related inelasticity of capacity with respect to radar separation in Equation 6-45.

6.3.4 Synthesising Departure Capacity Dynamics and Elasticities

6.3.4.1 Impact of Inter-departure Spacing

Like arrival capacity depends directly upon inter-arrival spacing, there is an intrinsic link relating departure capacity to weighted average inter-departure spacing. This functional relationship states that departure capacity γ_d is the inverse of the arithmetic mean of the time intervals between successive departures, τ_{dd} . Whilst referring to Equation 4-20, and whilst applying similar functional domain and image, together with the fleet homogeneity assumption, this functional relationship is formulated as

$$\gamma_d(\tau_{dd}) : \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^+ : \tau_{dd} \rightarrow \gamma_d(\tau_{dd}) = \frac{1}{\tau_{dd}}$$

Equation 6-46

The departure capacity dynamics δ_{γ_d} with respect to inter-departure spacing τ_{dd} is formulated by

$$\delta_{\gamma_d} : \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^- : \tau_{dd} \rightarrow \delta_{\gamma_d} = -\frac{1}{\tau_{dd}^2}$$

Equation 6-47

Like arrival capacity dynamics, it can be concluded that, for the same marginal fluctuation of inter-departure spacing, any division of inter-departure spacing by a factor of 2 multiplies the magnitude of the impact on departure capacity change by a factor of 4, and vice versa. For the same marginal fluctuation of inter-departure spacing, departure capacity is therefore more subject to change for low values of inter-departure spacing than high values. It can be further concluded that high-performance departure runways are expected to be less stable than low-performance runways.

The inter-departure spacing elasticity of capacity, noted $\varepsilon_{\gamma_d}(\tau_{dd})$, can be synthesized as

$$\varepsilon_{\gamma_d}(\tau_{dd}) : \mathfrak{R}_0^+ \rightarrow [-1] : \varepsilon_{\gamma_d}(\tau_{dd}) = -1$$

Equation 6-48

Like the inter-arrival spacing elasticity of arrival capacity, the inter-departure spacing elasticity of departure capacity is negatively unitary elastic; any percent increase (decrease) of inter-departure spacing has an impact on departure capacity equal to one percent decrease (increase).

The departure capacity function, as well as the departure capacity dynamics and elasticity with respect to inter-departure spacing, have therefore a similar shape to the ones represented in Figure 6-5.

6.3.4.2 Related Impact of Departure Runway Occupancy Time and Airborne Inter-Departure Separation Minima

This case is similar to that reported in Section 6.3.3.2, on the related impact of Arrival Runway Occupancy Time and Airborne In-trail Separation Minima. The functional relationship between capacity and both departure runway occupancy (DROT) and airborne inter-departure spacing can be formulated as follows:

$$\gamma_d(\tau^{drot}, \tau^{air}): \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^+ : (\tau^{drot}, \tau^{air}) \rightarrow \gamma_d(\tau^{drot}, \tau^{air}) = \begin{cases} \frac{1}{\tau^{drot}}, & \text{if } (\tau^{drot} \geq \tau^{air}) \\ \frac{1}{\tau^{air}}, & \text{if } (\tau^{drot} < \tau^{air}) \end{cases}$$

Equation 6-49

or, yet,

$$\gamma_d(\tau^{drot}, \tau^{air}) = \min\left(\frac{1}{\tau^{drot}}; \frac{1}{\tau^{air}}\right)$$

Equation 6-50

The departure capacity dynamics with respect to departure runway occupancy time and inter-departure spacing minima is synthesized as follows:

$$\overline{\delta}_{\gamma_d}(\tau^{drot}, \tau^{air}): \mathfrak{R}_0^+ \times \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^- : (\tau^{drot}, \tau^{air}) \rightarrow \overline{\delta}_{\gamma_d}(\tau^{drot}, \tau^{air}) \begin{cases} \left(\frac{-1}{(\tau^{drot})^2}; 0\right), & \forall \tau^{drot} \geq \tau^{air} \\ \left(0; \frac{-1}{(\tau^{air})^2}\right), & \forall \tau^{drot} < \tau^{air} \end{cases}$$

Equation 6-51

As far as the departure capacity elasticities are concerned, the DROT-elasticity of capacity is synthesized as follows:

$$\varepsilon_{\gamma_d}(\tau^{drot}) = \begin{cases} -1, \forall \tau^{drot} \geq \tau_{dd}^{air} \\ 0, \forall \tau^{drot} < \tau_{dd}^{air} \end{cases}$$

Equation 6-52

whilst the inter-departure spacing elasticity of departure capacity is formulated as

$$\varepsilon_{\gamma_d}(\tau_{dd}^{air}) = \begin{cases} 0, \forall \tau_{dd}^{air} \leq \tau^{drot} \\ -1, \forall \tau_{dd}^{air} > \tau^{drot} \end{cases}$$

Equation 6-53

These equations also enable us to conclude that departure runway occupancy time (DROT) has absolutely no impact on departure capacity below a certain threshold determined by inter-departure spacing minima. Vice versa, inter-departure spacing does not affect capacity when it is smaller than DROT. Departure capacity change is characterised by a clear change of direction at the ***DROT-Airborne Spacing Equity line*** at which the two capacity disrupters (DROT and airborne spacing) are equal. Yet, and as formulated in Equation 6-52 and Equation 6-53, the DROT-elasticity of departure capacity is negatively unitary elastic when DROT is greater than airborne spacing (i.e. $\varepsilon_{\gamma_d}(\tau^{drot}) = -1, \forall \tau^{drot} \geq \tau_{dd}^{air}$), and is perfectly inelastic when DROT is smaller than airborne spacing ($\varepsilon_{\gamma_d}(\tau^{drot}) = 0, \forall \tau^{drot} < \tau_{dd}^{air}$).

Conditional take-off clearance is an operational practice which consists of clearing a departure to line-up on the runway whilst the preceding aircraft is still taking-off, in order that it can start rolling to take-off as soon as the preceding aircraft reaches a safe distance driven by inter-departure separation minima. This saves time spent by a departure between crossing the active holding stop bar, and when the aircraft is fully lined up on the runway centreline, i.e. line-up time. In this latter case, DROT is reduced to take-off time only, rather than the sum of line-up time and take-off time. Further to the previous conclusion, it is demonstrated that this kind of practice is beneficial only when airborne inter-departure separation minima is smaller than departure runway occupancy. In the opposite case, departure runway occupancy has no impact on departure capacity, and conditional take-off clearance can only result in unnecessarily occupying the runway during a longer time. This operational case is another demonstration of the added value of the concepts of capacity dynamics and elasticities, in the assistance that they can provide in order to identify the

optimum conditions during which the conditional take-off clearance procedure can be optimally applied.

Similarly, departure capacity is **negatively unitary elastic** with respect to airborne in-trail spacing when airborne spacing is predominant compared to DROT (i.e. $\varepsilon_{\gamma_a}(\tau_{aa}^{air}) = -1, \forall \tau_{dd}^{air} > \tau^{drot}$); it is however **perfectly inelastic** when DROT is greater than airborne spacing ($\varepsilon_{\gamma_a}(\tau_{aa}^{air}) = 0, \forall \tau_{dd}^{air} \leq \tau^{drot}$).

6.4 Capacity Dynamics, Elasticities and Stability in Heterogeneous Fleet Mix Environment

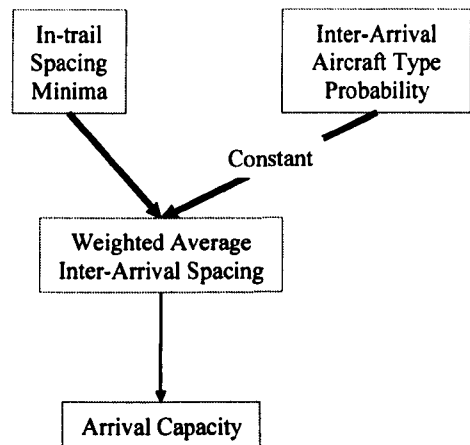
In Section 6.3.2, the fleet homogeneity assumption was made in order to keep the formulation of the capacity dynamics concepts as clear and understandable as possible. However, it is to be recognised that fleet is rarely homogeneous, and runways are usually operated to accommodate different types of aircraft. This leads airport modellers to cluster aircraft types into different classes, in order to enhance accuracy of the modelling results. This Section aims at demonstrating that it is possible to remove the fleet homogeneity assumption, although this makes the formulation of capacity dynamics, elasticities and stability more complex. The case that will be used for that purpose is the analysis of the impact of heterogeneous in-trail spacing minima on arrival capacity.

Inbound fleet is rarely homogenous and, most of the time, arrival runways are used to accommodate different types of aircraft that have their own constraints in terms of aerodynamics and ground performance and, consequently, in terms of airborne separation minima and runway occupancy. The time separation between two successive aircraft on final approach is usually determined by the type of leading aircraft because, on one side, the trailing aircraft needs to stay out of the turbulence generated by the preceding plane and, on the other, the trailing aircraft cannot be cleared to land without prior strong likelihood that the preceding aircraft will vacate the runway. That is the reason for which in-trail spacing is referred to as being a weighted average in the previous Section 6.3.3.1.

As reported in Section 4.2.2 regarding the basic concept of capacity, choosing the appropriate level of event disaggregation, or clustering, is paramount for reflecting the operational world as close as possible to reality, for the purposes of modelling accuracy maximisation. In reality, airport operations can be as complex as requiring a relatively deep

level of disaggregation. For instance, ICAO (1996) recommends clustering aircraft types into the three categories light, medium and heavy. However, there might be even more classes depending on special characteristics at the airport under investigation, such as runway exit used. But airport planners also need to bear in mind that too many clusters make modelling much more complex without bringing any added value in terms of results accuracy. A good level of disaggregation therefore needs to be identified.

As described at length in Section 6.3.1, the methodology used to formulate capacity dynamics and the various elasticities of capacity is based on the bottom-up analysis of the influence diagram, presented in Figure 6-4. If the fleet homogeneity assumption is removed, one can come back to the more complete runway capacity influence diagram illustrate in Figure 6-3. However, the traffic demand constancy assumption is maintained. This Section tackles the formulation of arrival capacity dynamics and elasticities of capacity by analysing the impact of heterogeneous fleet mix or level of disaggregation.



In order not to complicate the formulation of capacity dynamics and elasticity to excess, consider there exists only two different types of aircraft α and β . If two different aircraft classes are considered, then there is a combination of four different possible sequences of approaches, which are $\alpha\alpha$, $\alpha\beta$, $\beta\alpha$ and $\beta\beta$. Each of these possible sequences are characterised by a specific probability to appear, $p_{\alpha\alpha}$, $p_{\alpha\beta}$, $p_{\beta\alpha}$ and $p_{\beta\beta}$ such that $p_{\alpha\beta}$ represents the probability that an aircraft of type α is followed by aircraft type β . The probabilities $p_{\alpha\beta}$ are constant $\forall \alpha, \beta$, further to the traffic demand constancy assumption, as formulated in Section 6.3.1. Let $\tau_{\alpha\beta}$, the in-trail spacing minima required between these two types of aircraft α and β in such a way that the following approach aircraft β is not put in danger by the turbulence generated by the trailing aircraft α . In addition, the in-trail spacing minima $\tau_{\alpha\beta}$ is also a prerequisite to ensure safe operations and to comply with the single runway occupancy rule.

By further developing Equation 4-13, the in-trail spacing minima τ_{aa} between successive approaches referred to in Section 6.3.3.1 can be expressed as

$$\tau_{aa} = \sum_{\alpha, \beta} p_{\alpha\beta} \tau_{\alpha\beta} = p_{\alpha\alpha} \tau_{\alpha\alpha} + p_{\alpha\beta} \tau_{\alpha\beta} + p_{\beta\alpha} \tau_{\beta\alpha} + p_{\beta\beta} \tau_{\beta\beta}$$

Equation 6-54

in which the probabilities $p_{\alpha\beta}$ remain constant.

The functional relationship between in-trail spacing τ_{aa} and arrival capacity γ_a formulated in Equation 6-23 is a function of function $\gamma_a(\tau_{aa}(\tau_{\alpha\alpha}, \tau_{\alpha\beta}, \tau_{\beta\alpha}, \tau_{\beta\beta}))$, also denoted $(\gamma_a \circ \tau_{aa})(\tau_{\alpha\alpha}, \tau_{\alpha\beta}, \tau_{\beta\alpha}, \tau_{\beta\beta})$ or simply $\gamma_a(\tau_{\alpha\alpha}, \tau_{\alpha\beta}, \tau_{\beta\alpha}, \tau_{\beta\beta})$. Equation 6-23 can therefore be reformulated as follows:

$$\gamma_a(\tau_{\alpha\alpha}, \tau_{\alpha\beta}, \tau_{\beta\alpha}, \tau_{\beta\beta}) : \mathfrak{R}_0^+ \rightarrow \mathfrak{R}_0^+ : \tau_{\alpha\beta} \rightarrow \gamma_a(\tau_{\alpha\alpha}, \tau_{\alpha\beta}, \tau_{\beta\alpha}, \tau_{\beta\beta}) = \frac{1}{\sum_{\alpha, \beta} p_{\alpha\beta} \tau_{\alpha\beta}} ; \forall \alpha, \beta$$

Equation 6-55

Based on the appropriate differentiation techniques, and the chain rule for differentiation in particular, synthesising the arrival capacity dynamics $\overline{\delta_{\gamma_a}}$ with respect to heterogeneous in-trail spacing $\tau_{aa} = \sum_{\alpha, \beta} p_{\alpha\beta} \tau_{\alpha\beta}$ results in the following vector:

$$\overline{\delta_{\gamma_a}(\tau_{\alpha\alpha}, \tau_{\alpha\beta}, \tau_{\beta\alpha}, \tau_{\beta\beta})} = \left(-\frac{p_{\alpha\alpha}}{\tau_{aa}^2}, -\frac{p_{\alpha\beta}}{\tau_{aa}^2}, -\frac{p_{\beta\alpha}}{\tau_{aa}^2}, -\frac{p_{\beta\beta}}{\tau_{aa}^2} \right)$$

Equation 6-56

The total probability rule states that the sum of the probabilities $p_{\alpha\beta}$ equals 1. Consequently, it is to be noted that **the sum of all the elements of the capacity dynamics $\overline{\delta_{\gamma_a}(\tau_{\alpha\alpha}, \tau_{\alpha\beta}, \tau_{\beta\alpha}, \tau_{\beta\beta})}$ with respect to the specific in-trail spacing $\tau_{\alpha\beta}, (\forall \alpha, \beta)$, equals the capacity dynamics $\delta_{\gamma_a}(\tau_{aa})$ with respect to the weighted average in-trail spacing:**

$$\sum_{\alpha\beta} P_{\alpha\beta} = 1 \Leftrightarrow \sum_{\alpha\beta} \delta_{\gamma_a}(\tau_{\alpha\beta}) = \delta_{\gamma_a}(\tau_{aa}), \forall \alpha, \beta$$

Equation 6-57

This latter rule also enables us to conclude that each element $\delta_{\gamma_a}(\tau_{\alpha\beta})$ of the capacity dynamics $\overline{\delta_{\gamma_a}(\tau_{\alpha\alpha}, \tau_{\alpha\beta}, \tau_{\beta\alpha}, \tau_{\beta\beta})}$ contributes to the global instantaneous rate of change of arrival capacity $\delta_{\gamma_a}(\tau_{aa})$ on a pro rata basis, i.e. proportionally to the probability $P_{\alpha\beta}$ that the sequence $\alpha\beta$ appears.

Capacity dynamics provides the direction in which capacity changes most quickly as well as a measure of the magnitude of the capacity slope in that direction.

The magnitude of capacity dynamics is the Euclidian length given by:

$$\|\overline{\delta_{\gamma_a}}\| = \frac{\sqrt{P_{\alpha\alpha}^2 + P_{\alpha\beta}^2 + P_{\beta\alpha}^2 + P_{\beta\beta}^2}}{(P_{\alpha\alpha}\tau_{\alpha\alpha} + P_{\alpha\beta}\tau_{\alpha\beta} + P_{\beta\alpha}\tau_{\beta\alpha} + P_{\beta\beta}\tau_{\beta\beta})^2}$$

Equation 6-58

When two different aircraft classes are considered, then there is a combination of four different possible sequences of approaches, each of them being characterised by a specific in-trail spacing minima $\tau_{\alpha\alpha}$, $\tau_{\alpha\beta}$, $\tau_{\beta\alpha}$ and $\tau_{\beta\beta}$. Consequently, this results in a combination of four possible in-trail spacing elasticities of capacity, which are formulated as follows, based on the basic Equation 6-10:

$$\begin{cases} \varepsilon_{\gamma_a}(\tau_{\alpha\alpha}) = \frac{\tau_{\alpha\alpha}}{\gamma_a} \times \left(-\frac{P_{\alpha\alpha}}{\tau_{\alpha\alpha}^2} \right) \\ \varepsilon_{\gamma_a}(\tau_{\alpha\beta}) = \frac{\tau_{\alpha\beta}}{\gamma_a} \times \left(-\frac{P_{\alpha\beta}}{\tau_{\alpha\alpha}^2} \right) \\ \varepsilon_{\gamma_a}(\tau_{\beta\alpha}) = \frac{\tau_{\beta\alpha}}{\gamma_a} \times \left(-\frac{P_{\beta\alpha}}{\tau_{\alpha\alpha}^2} \right) \\ \varepsilon_{\gamma_a}(\tau_{\beta\beta}) = \frac{\tau_{\beta\beta}}{\gamma_a} \times \left(-\frac{P_{\beta\beta}}{\tau_{\alpha\alpha}^2} \right) \end{cases}$$

Equation 6-59

Yet, the arrival capacity is the inverse of the weighted average in-trail spacing (Equation 6-23) and, therefore, these various elasticities can be reduced to

$$\begin{cases} \varepsilon_{\gamma_a}(\tau_{\alpha\alpha}) = -\frac{P_{\alpha\alpha}\tau_{\alpha\alpha}}{\tau_{aa}} \\ \varepsilon_{\gamma_a}(\tau_{\alpha\beta}) = -\frac{P_{\alpha\beta}\tau_{\alpha\beta}}{\tau_{aa}} \\ \varepsilon_{\gamma_a}(\tau_{\beta\alpha}) = -\frac{P_{\beta\alpha}\tau_{\beta\alpha}}{\tau_{aa}} \\ \varepsilon_{\gamma_a}(\tau_{\beta\beta}) = -\frac{P_{\beta\beta}\tau_{\beta\beta}}{\tau_{aa}} \end{cases}$$

Equation 6-60

It can be concluded that, within a heterogeneous fleet environment, the fluctuation of in-trail spacing for a given sequence of approaches contributes on a pro rata basis to the global arrival capacity dynamics. This pro rata basis is calculated as the product of the probability that a particular sequence occurs and the in-trail spacing required by that sequence. The same phenomenon is also valid for departure capacity with respect to a heterogeneous outbound fleet.

6.5 Capacity Stability and Robustness

In general, stability measures how robust a system is with respect to external forces, or how resistant it is to potential change of some variables of interest. The **stability** concept, also called *constancy* or *persistence* in some fields, provides a measure of the system's response to some perturbation. Stability is often related to both *resistance* that is a measure of how little a given variable of interest changes in response to stress or external pressures, and *inertia* that represents the characteristic of the system to change at some rate that is relatively constant in the face of external fluctuation.

As a concrete skyscraper with ball-and-socket joints for foundations is robust because it can resist earthquakes, capacity is intuitively robust if it can resist the fluctuation of its various disrupters. If so, capacity can also be considered as being stable.

It is shown in the previous Sections how capacity can fluctuate depending on the dynamics of the various factors that affect it. It is also shown in Sections 6.3.3.1 and 6.3.4.1 how any division of in-trail or inter-departure spacing by a factor of 2 multiplies the magnitude of the impact on capacity change by a factor of 4, for the same marginal fluctuation of in-trail or inter-departure spacing. The example of 1"- marginal fluctuation of in-trail spacing was given for 40" and 80" in-trail spacing. Capacity dynamics is -0.56 arrivals/hour/sec around 80" in-trail spacing, whilst it is increased to -2.25 arrivals/hour/sec around 40". In other words, the same marginal fluctuation of in-trail spacing has 4 times more impact on capacity than for capacity resulting from double in-trail spacing. It can also be concluded that, although capacity is doubled, capacity is 4 times less stable or robust.

Capacity predictability is certainly a key measure of the intrinsic quality of planning, as mentioned in Section 2.3.3. Capacity fluctuation has a major impact on the accuracy of slot allocation and slot scheduling. In order to ensure planning accuracy of any economic system, it is definitely required to measure the robustness of capacity of that economic system. For airports in particular, any airport planner for whom planning accuracy is a major concern should raise the following question: *"How robust is airport capacity, given all the various factors that may affect it due to their fluctuations?"*. It is obvious that the more capacity fluctuates, and the less accurate airport planning can be, ... unless the risks of fluctuation can be rigorously quantified and controlled with appropriate mitigation plans.

With the same airport planning methodology, planning is therefore expected to be more robust if it is based on a low-performing system than for a high-performance system, because the high-performing system is subject to less stability. This is purely paradoxical because the fact that the more a system is expected to be used close to saturation, the better it should be expected to perform and, therefore, the more accurate the planning should be. This is a clear paradox between capacity enhancement and capacity stability.

This **capacity/stability paradox** can be better analysed with the capacity dynamics concept. With capacity dynamics, it is possible to measure how robust capacity is, regarding the potential fluctuation of some of its disrupters. The capacity stability μ_γ with respect to a set $\{f_1, \dots, f_i, \dots, f_n\}$ of capacity disrupters, noted $\mu_\gamma(f_1, \dots, f_i, \dots, f_n)$, is a performance indicator that can be formulated as the inverse of capacity dynamics magnitude with respect to this same set of capacity disrupters:

$$\mu_{\gamma}(f_1, \dots, f_i, \dots, f_n) = \frac{1}{|\delta_{\gamma}(f_1, \dots, f_i, \dots, f_n)|} = \frac{1}{\|\delta_{\gamma}(f_1, \dots, f_i, \dots, f_n)\|}$$

Equation 6-61

Capacity stability measures the inertia of capacity to change, i.e. its robustness regarding changes. The more stable capacity is, the less it is responsive to fluctuation of its disrupters. Coming back to our example, capacity stability at 80" in-trail spacing is 1.8 whilst it decreases to 0.44 for 40" in-trail spacing.

The correlation between capacity fluctuation (i.e. capacity dynamics) and delay is beyond the scope of this thesis, but should certainly be subject to further research in order to confirm that the probability of delay growth is related to capacity robustness and stability. At this stage, the concepts of capacity dynamics and elasticities however enable us to do indefinite soul-searching at maximising capacity, and question the ultimate goal of capacity enhancement.

The risk of delay, whatever the source of delay, should be analysed, qualified and quantified by airport planners. The quantification and analysis of capacity dynamics, elasticities and stability with respect to the various factors that might affect capacity enable action plans to be drafted in order to mitigate the risk of delay.

Should capacity be enhanced despite all opposition, the results of a classical capacity analysis, as good as it could be, prove to be insufficient. It turns out that capacity stability should be quantified and fully analysed to be part of any capacity enhancement plan.

6.6 Conclusion

It can be concluded that the two concepts of elasticity of capacity and capacity dynamics provide airport planners with a new perspective on capacity. Elasticity of capacity with respect to its various capacity disrupters measure individual responsiveness of capacity to fluctuation of each of those disrupters considered in isolation. The concept of capacity dynamics provides a measure of the magnitude and direction in which capacity changes most quickly. In other words, capacity dynamics provides a global measure of capacity stability or robustness given all the factors that might affect it, considered together, whilst elasticity of capacity provides a measure of capacity stability or robustness with respect to

individual capacity disrupters. These two concepts are complementary in order to identify capacity robustness and responsiveness to the fluctuation of the environment in which capacity is operated and, most importantly, managed.

The traditional and classical concept of capacity envelope, which is described in Section 4.3.4 and used since the 1970's, is quite limiting in the sense that it reflects the trade-off between arrival and departure capacity only. It is demonstrated in this Section that capacity is not limited to this trade-off, and that the capacity envelope can therefore not be represented by a 2-dimensional plane, but is rather a surface with variable curvature, limited by the field of capacity change potential.

A major conclusion can be drawn from this research, that is **the more efficiently a runway system is operated, the more sensitive the system capacity is to fluctuation of some of its capacity disrupters, i.e. the less stable it is** and therefore the more likely delay is to be increased. This conclusion is all the more important for those airports that are operated with 2.5 NM on final approach. Given this conclusion, the safety case should be all the more robust for such operational practices. This also shows that capacity dynamics and stability can be considered as a real performance indicator of the assurance that a planned service can be really and precisely accommodated.

Based on this conclusion, airport planners should raise the question whether it is preferable to maximise capacity to the detriment of capacity stability, or if it is better to favour capacity stability to the detriment of capacity itself in order to keep the risk of delay to a minimum level. The wiser decision would probably consist of achieving a trade-off between capacity maximisation and capacity dynamics that reflects its stability, based on an acceptable delay tolerance. Further research should consist of correlating the capacity dynamics and delay records at various airports in Europe in order to strengthen this conclusion.

It can be concluded that the three concepts of capacity dynamics, elasticities and stability provide airport planners and managers with a quantification of the global sensitivity of factors affecting operational capacity, in other words, capacity robustness. When capacity modelling is used for the purpose of capacity declaration, the capacity dynamics concepts enable airport planners and operators to identify how robust declared capacity is when based on one global value, given all the various factors that may affect it, due to their dynamic and stochastic fluctuation.

Chapter 7 - Capacity Dynamics, Elasticities and Stability: A Case Study

The objective of this new case study to be presented in this chapter is threefold: first, to pursue the capacity analysis further, by applying the two concepts of capacity dynamics and elasticities of capacity, formulated in Chapter 6 and, second, to provide airport planners and decision-makers with a global picture of the factors that most affect capacity, through the concept of the **airport planning compass**. Last, capacity stability will be formulated as a performance indicator of capacity robustness, i.e. inertia to generate delay.

In order to illustrate the concepts as clearly as possible, this new case study will be based on the same assumptions of traffic demand constancy and fleet homogeneity, described in Section 6.3.2. The heterogeneous fleet mix case described in Section 6.4 will nevertheless be illustrated as well.

7.1 Arrival Capacity

7.1.1 Impact of Inter-arrival Spacing

Based on the processing of the validated input, it was concluded in Section 5.3.3.1 that the resulting weighted average in-trail spacing time between two successive approaches towards RWY 25R is 80.13". Based on the functional relationship between in-trail spacing τ_{aa} and capacity γ_a synthesized in Equation 6-23, and by applying the right transformation of dimensions (units), this results in an arrival capacity of 44.93 arrivals per hour per runway.

Let in-trail spacing fluctuate between a hypothetical minimum value of 30" up to about twice its current value (i.e. 2'40"). The range of fluctuation [30";160"] looks relatively wide and somewhat unrealistic; nothing can however be concluded at this stage of the analysis. While referring to the *image focus principle* defined in Section 6.3.1, the higher one goes into the tree-representation of the capacity influence diagram, the more precise the intervals of fluctuation can be stated. At this early stage of the analysis, it is therefore preferable to consider fluctuation intervals that are large enough rather than being too narrow; these intervals will be refined further on as better operational knowledge of the independent capacity disrupters will appear.

Based on the capacity functional relationship (Equation 6-23), the fluctuation of in-trail spacing within the interval [30";160"] entails arrival capacity changes from 22.5 arrivals per hour for the highest limit of in-trail spacing (160") to 120 arrivals per hour for the lowest limit of in-trail spacing (30"), which can be summarised as follows:

$$\gamma_a(\tau_{aa}): [30;160] \rightarrow [120;22.5] \rightarrow \gamma_a(\tau_{aa}) = 3600 / \tau_{aa}$$

In the previous functional relationship, the constant 3600 enables seconds to be converted into hours.

The functional relationship between in-trail spacing and capacity over the domain [30";160"] is shown in the top subplot of Figure 7-1. The top subplot of Figure 7-2 shows a zoom of the capacity function over the sub-domain [70";90"] in the closer vicinity of the operational value of 80.13".

The capacity dynamics with respect to in-trail spacing can be calculated with Equation 6-25.

The capacity dynamics at the operational point (80.13;44.93) is $\frac{-3600}{80.13^2} = -0.5607$, which represents the instantaneous rate of capacity change at the operational point. This means that any increase (decrease) of in-trail spacing by 1" leads to a decrease (increase) of capacity by 0.56 arrivals per hour. This is illustrated in Figure 7-2 by the two points (79.13;45.49) and (81.13;44.37). The unit of capacity dynamics is the number of arrivals per hour per second of in-trail spacing change, i.e. arrivals/hour/sec.

As formulated in Equation 6-25 and shown in Figure 7-1, this rate of change is not constant, and increases in a hyperbolic way when in-trail spacing decreases. Around 160" in-trail spacing, capacity dynamics is -0.14 arrivals/hour/sec and therefore, any marginal change of in-trail spacing (1") in the vicinity of 160" leads to a capacity change -0.14 arrivals/hour only. However, if in-trail separation is reduced to 30", any new marginal fluctuation of in-trail spacing by 1 second in the vicinity of this 30"-value leads to a change of capacity by -4 arrivals/hour. If in-trail spacing is half its operational value, i.e. 40.07", capacity dynamics becomes -2.24, that is four times the capacity dynamics at the operational value. And vice versa, doubling in-trail spacing (160") results in a capacity dynamics value that is a quarter of its original value (-0.14 w.r.t. -0.56)). As concluded in Section 6.3.3.1, **any division of in-**

trail spacing by a factor of 2 multiplies arrival capacity dynamics by a factor of 4, and vice versa.

Most importantly, it can be concluded that capacity is less stable for lower values, and more robust for greater values of in-trail spacing. At the operational point (80.13;44.93), the capacity stability indicator formulated in Equation 6-61 gives a value of $\left| \frac{1}{-0.5607} \right| = 1.7835$

arrivals/hour/sec. For 30"-in-trail spacing, that reflects much better performance, capacity stability drops to $\left| \frac{1}{-4} \right| = 0.25$ arrivals/hour/sec. On the other side, capacity stability grows to

$\left| \frac{1}{-0.1406} \right| = 7.1124$ arrivals/hour/sec for the greater value of in-trail spacing of 160". This

case study illustrates the general conclusion stated in Section 6.3.3.1, that **the more efficiently a runway system is operated, the more sensitive its capacity is to fluctuation of some of its capacity disrupters, i.e. capacity is less stable.**

The elasticity concept expresses the rate at which a quantity changes with respect to the change in another quantity, on which it has a functional relationship. The inter-arrival spacing elasticity of capacity expresses the ratio of the percentage change in capacity with respect to the percentage fluctuation of in-trail spacing. For instance, let in-trail spacing decrease by 1%, i.e. from 80.13" to 79.33". Based on the general formulation of capacity in Equation 6-23, the capacity with respect to 79.33"-in-trail spacing is given by $\frac{3600}{79.33} = 45.38$

arrivals/hour, as shown in Figure 7-2. Compared to capacity at the operational point, this 1%-decrease of in-trail spacing indeed leads to $\left(\frac{45.38 - 44.93}{44.93} \right) = 1\%$ increase in

arrival capacity, which confirms elasticity. In-trail spacing elasticity of capacity can also be calculated while applying the general formulation of elasticity, in Equation 6-9, that results in

$$\frac{\left(\frac{44.93 - 45.38}{44.93} \right)}{\left(\frac{80.13 - 79.33}{80.13} \right)} = -1. \text{ It can be concluded that the in-trail spacing elasticity of arrival}$$

capacity is -1 at the operational point (80.13;44.93).

Equation 6-26 states that in-trail elasticity of arrival capacity constantly equals -1, as shown in Figure 7-1 and Figure 7-2. This confirms that any percent increase (decrease) of in-trail

spacing has an impact on arrival capacity equal to a one percent decrease (increase). Consequently, in-trail elasticity of arrival capacity is said to be negatively unitary.

Because it represents a ratio of two percentage changes, the elasticity of capacity is a real number and not a vector in opposite to capacity dynamics. It is in addition dimensionless.

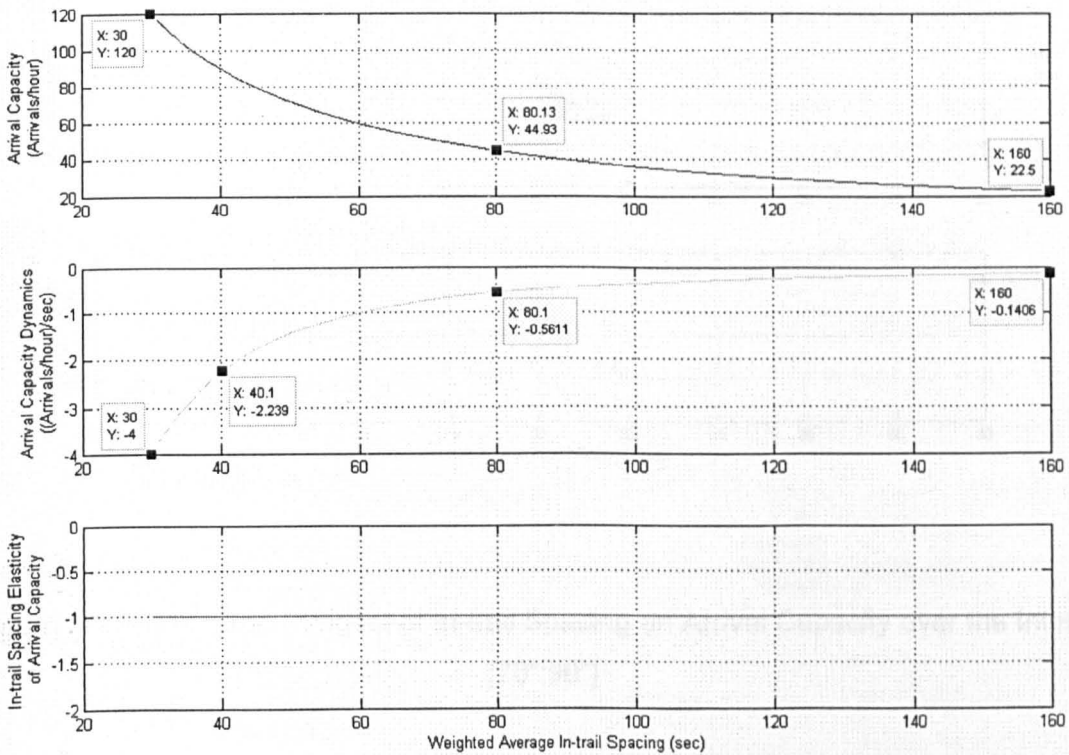


Figure 7-1 – RWY 25L - Impact of In-trail Spacing on Arrival Capacity over the Interval [30";160"]

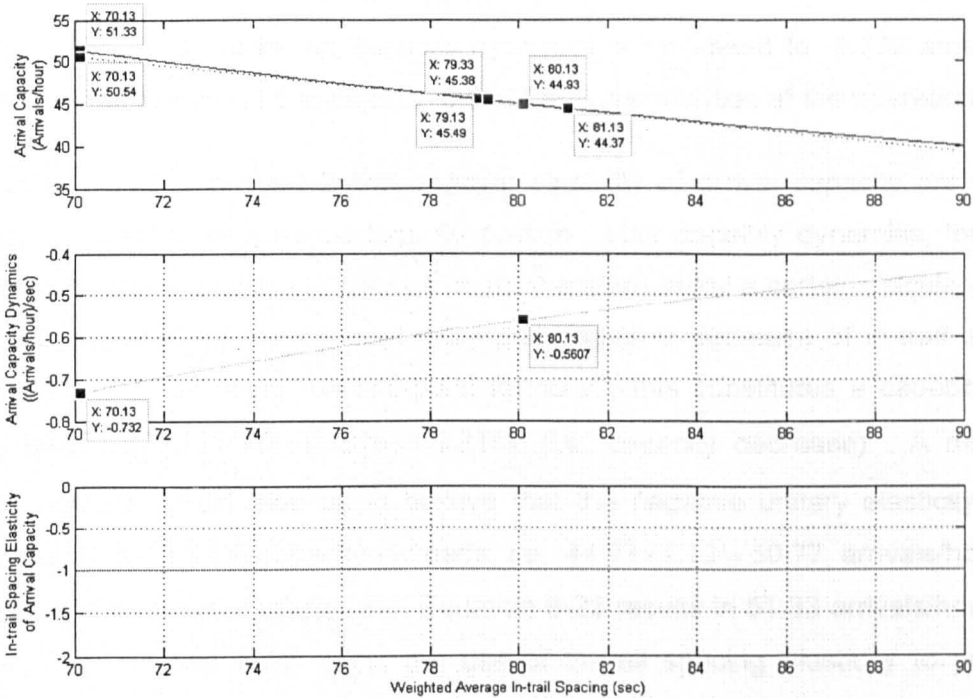


Figure 7-2 – RWY 25L - Impact of In-trail Spacing on Arrival Capacity over the Interval [70";90"]

7.1.2 Intrinsic Error due to Misuse of the Concepts

Capacity dynamics provides the instantaneous rate of capacity change, i.e. a good estimate of marginal fluctuation in the vicinity of a given point. Capacity dynamics represents the slope of the tangent at that specific point. This tangent is illustrated in Figure 7-2 by the dotted line for the operational point (80.13;44.93). The use of the capacity dynamics concept for capacity extrapolation therefore entails a certain calculation error and constitutes a misuse of the concept. Consider for instance a decrease of in-trail spacing by 10", which is no longer marginal. If capacity dynamics were used for the calculation of capacity with respect to 70.13" in-trail spacing, this capacity would be the capacity at the operational point (i.e. 44.93) plus 10 times the capacity dynamics at the operational point, i.e.

$$\gamma_a(70.13'') = 44.93 - (10 \times (-0.5607)) = 50.54 \text{ arrivals/hour.}$$

The real capacity value calculated with Equation 6-23 however results in $\frac{-3600}{70.13^2} = 51.33$ arrivals/hour. This misuse

consequently shows an absolute capacity error of 0.79 arrivals/hour, i.e. 1.8% and an even greater relative error of $1 - \frac{(50.54 - 44.93)}{(51.33 - 44.93)} = 12\%$. This error comes from the fact that capacity dynamics is not linear; capacity dynamics is increased to -0.732 arrivals/hour/sec for 70.13" in-trail spacing, compared to -0.5607 arrivals/hour/sec at the operational point.

It is also to be stressed that in-trail spacing elasticity of arrival capacity provides a good estimate of instantaneous percentage fluctuation. Like capacity dynamics, the use of the elasticity concept for bigger fluctuations might therefore entail a certain calculation error and constitutes a misuse of the concept. Consider again a decrease of in-trail spacing from 80.13" to 70.13". By using the mid-point formula¹⁸, this constitutes a capacity change of $(70.13 - 80.13) / ((70.13 + 80.13) / 2) = -13.31\%$ (i.e. capacity decrease). A misuse of the elasticity concept would lead us to believe that the negative unitary elasticity of capacity would result in a 13.31% capacity increase, i.e. $44.93 \times 1.13 = 50.77$ arrivals/hour, although the calculation of arrival capacity with Equation 6-23 results in 51.33 arrivals/hour, as shown in Figure 7-2. In this latter case, the use of in-trail spacing elasticity to project arrival capacity leads to an error of 0.56 arrivals/hour, or 1.1%.

The reader needs to bear in mind that this constitutes a misuse of these concepts, coming from a more general misuse of the mathematical concept of differentiation.

Should elasticity of capacity be used against all opposition to project capacity, a better capacity approximation can be provided through the application of the financial rule of compound interest for constant interest rate. Based on the elasticity of capacity, the projected capacity for 70.13" in-trail spacing can be calculated as $44.93 \times (1 + 0.01)^{13.31} = 51.3$ arrivals/hour. In a more general way, the change of the original capacity $\gamma(\tau)$ to capacity $\gamma(\tau')$ with respect to the fluctuation of in-trail spacing from the original value τ to a value τ' , based on the elasticity of capacity $\varepsilon_\gamma(\tau)$, can be better approximated to:

¹⁸ The normal manner of percent change calculation is based on the original point. In this case, this results in $(70.13 - 80.13) / 80.13 = -12.48\%$. The midpoint formula has the benefit that a change from a value a to a value b is the exact negative of the change from b to a. In our example, the midpoint percentage is the exact negative of the change from 70.13" to 80.13", whereas the normal percentage change would be $(80.13 - 70.13) / 70.13 = 14.26\%$.

$$\gamma(\tau') = \gamma(\tau) \times (1 + \varepsilon_\gamma(\tau))^{2 \times (\tau - \tau')} / (\tau + \tau')$$

Equation 7-1

In brief, the capacity dynamics and elasticity concepts are developed to quantify the local instantaneous rate of capacity change and to provide robust estimates of local marginal fluctuations. However, misusing these concepts by extrapolating capacity entails a certain calculation error detrimental to the quality of information.

7.1.3 Impact of Heterogeneous In-trail Spacing

The calculation of arrival capacity which was analysed in Section 5.3.3.1 is based on a given inbound fleet mix reported in Table 5-5. The purpose of this Section is to illustrate the conclusions for capacity dynamics and elasticities regarding heterogeneous in-trail spacing, as formulated in Section 6.4.

According to this inbound fleet mix and based on the aircraft classification adopted in Section 5.2.4, the probability that an aircraft type follows any other aircraft type is given by the following probability matrix:

$$P = \begin{bmatrix} 0.0000 & 0.0002 & 0.0055 & 0.0001 & 0.0002 \\ 0.0002 & 0.0009 & 0.0274 & 0.0004 & 0.0011 \\ 0.0055 & 0.0274 & 0.8354 & 0.0137 & 0.0320 \\ 0.0001 & 0.0004 & 0.0137 & 0.0002 & 0.0005 \\ 0.0002 & 0.0011 & 0.0320 & 0.0005 & 0.0012 \end{bmatrix}$$

In this matrix, the element $p_{ij} = p_{i,j}$ represents the probability that an aircraft of type i is followed by an aircraft of type j . The rows represent the leading aircraft, in the following order : light (L), medium turbo-prop (MT), medium jets (MJ), medium-heavies (MH) and heavies (H). The columns represent the following aircraft, in the same order. For instance, the element $p_{3,2} = 2.74\%$ represents the probability $p_{MJ,MT}$ that an aircraft of type medium jet (MJ) is followed by a medium turbo-prop (MT).

Based on the same convention, the time-based in-trail spacing minima between these successive aircraft types is given by the following matrix, in which the element $\tau_{ij} = \tau_{i,j}$ represents the minimum in-trail spacing required when an aircraft of type i is followed by an

aircraft of type j . Equation 4-19 enables us to calculate this matrix for each sequence of approaches, based on the wake vortex separation minima, radar separation and approach speeds. With the input data described in Section 5.3.2, the airborne in-trail spacing minima matrix is as follows,

$$T = \begin{bmatrix} 86.4000 & 80.5970 & 77.1429 & 81.8182 & 73.9726 \\ 144.0000 & 80.5970 & 77.1429 & 81.8182 & 73.9726 \\ 144.0000 & 80.5970 & 77.1429 & 81.8182 & 73.9726 \\ 172.8000 & 134.3284 & 128.5714 & 136.3636 & 98.6301 \\ 172.8000 & 134.3284 & 128.5714 & 136.3636 & 98.6301 \end{bmatrix}$$

This means that, for instance, the minimum in-trail spacing time required between a medium-jet followed by medium turbo-prop is $\tau_{MJ,MT} = \tau_{3,2} = 80.6''$.

The arrival capacity dynamics $\overrightarrow{\delta_{\gamma_a}}$ with respect to heterogeneous in-trail spacing was formulated in Equation 4-14. For n different aircraft classes, the arrival capacity dynamics $\overrightarrow{\delta_{\gamma_a}}$ is a vector composed of $n \times n$ components, each component reflecting the dynamics of arrival capacity with respect to a specific sequence of landings. For the five categories of aircraft types considered in this study, capacity dynamics is therefore a vector composed of 25 elements; and each of these elements takes effects in the marginal change of capacity.

At the operational point (80.13;44.93), the capacity dynamics with respect to the various in-trail spacing minima is therefore defined by

$$\overrightarrow{\delta_{\gamma_a}(\tau_{ij})} = \begin{pmatrix} -0.0000 & -0.0001 & -0.0031 & -0.0001 & -0.0001 & \dots \\ -0.0001 & -0.0005 & -0.0154 & -0.0003 & -0.0006 & \dots \\ -0.0031 & -0.0154 & -0.4684 & -0.0077 & -0.0179 & \dots \\ -0.0001 & -0.0003 & -0.0077 & -0.0001 & -0.0003 & \dots \\ -0.0001 & -0.0006 & -0.0179 & -0.0003 & -0.0007 & \dots \end{pmatrix}$$

The vector $\overrightarrow{\delta_{\gamma_a}(\tau_{ij})}$ provides the instantaneous rate of capacity change with respect to the marginal fluctuation of each in-trail spacing τ_{ij} . For instance, should the sequence between successive medium jets be considered, any increase (decrease) of in-trail spacing between medium jets by 1" leads to a decrease (increase) of capacity by -0.4684 arrivals/hour. Indeed, decreasing in-trail spacing between medium jets by 1" results in a MJ-MJ in-trail

spacing of 76.1429" instead of 77.1429", that results in weighted average in-trail spacing minima of 79.30" instead of 80.13" and, consequently, in an arrival capacity of 45.3964 arrivals/hour instead of 44.9279. In conclusion, the 1"-decrease of in-trail spacing between medium jets results in an increase of arrival capacity by 0.4684 arrivals/hour/sec, as calculated by the dynamics capacity $\overline{\delta_{\gamma_a}(\tau_{3,3})}$

As calculated in the previous Section 7.1, the capacity dynamics at the operational point (80.13;44.93) is $\frac{-3600}{80.13^2} = -0.5607$ arrivals/hour/sec, and represents the instantaneous rate of capacity change at the operational point. Equation 6-57 states that the sum of all the elements of the capacity dynamics with respect to the specific in-trail spacing equals the capacity dynamics with respect to the weighted average in-trail spacing. This rule can be verified as the sum of all the elements of the capacity dynamics $\overline{\delta_{\gamma_a}(\tau_{ij})}$ calculated here, and obviously equals -0.5607 arrivals/hour/sec. This also means that each element (i, j) of the capacity dynamics $\overline{\delta_{\gamma_a}(\tau_{ij})}$ contributes to the global instantaneous rate of change of arrival capacity $\delta_{\gamma_a}(\tau_{aa}) = -0.5607$ on a pro rata basis, i.e. proportionally to the probability $p_{i,j}$ that the sequence (i, j) appears. For instance, the sequence (MJ,MJ) composed of successive medium jets contributes for -0.4684 arrivals/hour/sec into the global instantaneous rate of change of -0.5607 arrivals/hour/sec. In other words, the sequence (MJ,MJ) contributes $\frac{-0.4684}{-0.5607} = 83.54\% = p_{MJ,MJ} = P_{3,3}$ of the global arrival capacity change.

The length of the capacity dynamics vector $\overline{\delta_{\gamma_a}(\tau_{ij})}$ defined here results in 0.4697.

The elasticity of capacity with respect to heterogeneous in-trail spacing can be represented by a matrix $E_{\gamma_a}(\tau_{ij})$ such that each element $\varepsilon_{\gamma_a}(\tau_{ij})$ represents the elasticity of arrival capacity with respect to the in-trail spacing τ_{ij} between an aircraft type i followed by an aircraft j . Each of the elements $\varepsilon_{\gamma_a}(\tau_{ij})$ can be calculated based on Equation 6-60. The elasticity matrix of capacity with respect to heterogeneous in-trail spacing is

$$E_{\gamma_a}(\tau_{ij}) = \begin{bmatrix} -0.0000 & -0.0002 & -0.0053 & -0.0001 & -0.0002 \\ -0.0003 & -0.0009 & -0.0264 & -0.0005 & -0.0010 \\ -0.0099 & -0.0276 & -0.8043 & -0.0140 & -0.0295 \\ -0.0002 & -0.0008 & -0.0220 & -0.0004 & -0.0006 \\ -0.0005 & -0.0018 & -0.0513 & -0.0009 & -0.0015 \end{bmatrix}$$

In general, any 1%-decrease (increase) of an element (i, j) of the elasticity matrix of capacity $E_{\gamma_a}(\tau_{ij})$ entails an increase (decrease) in capacity by $\varepsilon_{\gamma_a}(\tau_{ij})\%$. Whilst referring to the same example of the impact of the MJ-MJ sequence, this means that any 1%-decrease of the in-trail spacing minima between successive medium jets results in 0.8043% increase in arrival capacity.

It is to be noted that the sum of all the elements of this elasticity matrix equals -1, which is indeed the global elasticity of capacity with respect to weighted average in-trail spacing.

7.1.4 Related Impact of Arrival Runway Occupancy Time and Airborne In-trail Separation Minima

In order to reach a higher level of accuracy, disaggregation of aircraft type into 5 different classes was used in the case study performed in Chapter 5 as well as in Section 7.1.2 above. However, the aim of the analysis in this Section is to illustrate the related impact of arrival runway occupancy time and airborne in-trail separation formulated previously in Section 6.3.3.2. In order to be as clear as possible in this illustration through a case study, the fleet homogeneity assumption will be maintained, and the capacity dynamics and elasticities with respect to runway occupancy time and airborne in-trail spacing minima are calculated independently of aircraft type, i.e. with no aircraft type disaggregation.

Based on the data collected and reported in Table 5-5, the weighted average arrival runway occupancy time (AROT) is 50.46" on RWY 25R. In a similar way, the weighted average airborne in-trail spacing minima is 80.13", and is referred to as the airborne in-trail spacing minima hereafter. Based on Equation 6-29, arrival capacity is given by

$$\frac{3600}{\max(50.46;80.13)} = 44.93 \text{ arrivals/hour.}$$

In Table 5-5, it can be seen that AROT can fluctuate between 40" and 100". In the airborne in-trail spacing minima matrix T calculated in Section 7.1.3, the airborne in-trail spacing

minima ranges from 70" for favourable arrivals sequences up to 175" for the most unfavourable sequences. Based on the same Equation 6-29, but over these two domains of AROT and airborne in-trail spacing, the hourly arrival capacity can vary between 51.43 and 20.57 arrivals.

Whilst applying Equation 6-31, the arrival capacity dynamics with respect to airborne in-trail spacing minima is -0.56 arrivals/hour/sec, whilst the dynamics with respect to AROT is null. The gradient representation of the arrival capacity dynamics with respect to both AROT and airborne in-trail spacing is represented in Figure 7-3. The arrows indicate the directions in which the capacity changes. The capacity isobars are represented in blue per tens of arrivals/hour. The thick red line represents the AROT-Airborne Spacing Equity line. As mentioned, the arrival capacity dynamics is (0;-0.56) at the operational point

$$\left(\tau^{arot}, \tau_{aa}^{air} \right) = (50.46; 80.13).$$

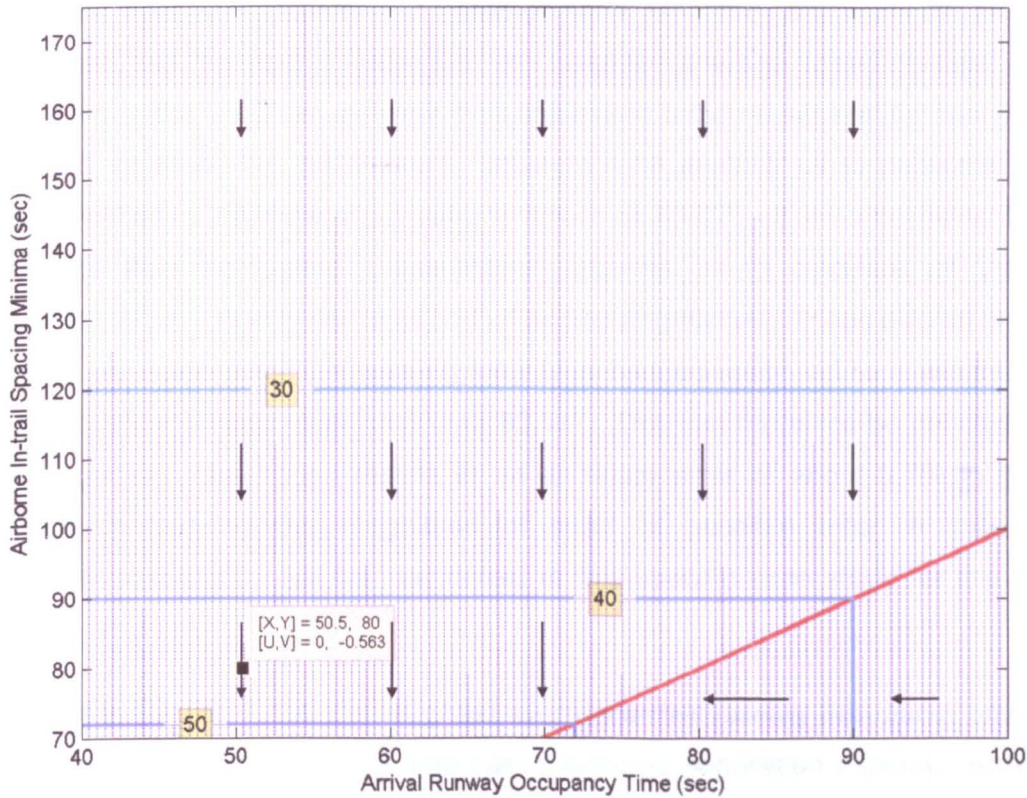


Figure 7-3 – Case Study - Gradient Representation of Arrival Capacity Dynamics w.r.t. AROT and Airborne In-trail Spacing Minima

It is clear from this representation that AROT has no impact on arrival capacity, should the airborne in-trail spacing minima be in the interval [70";175"], unless airborne in-trail spacing is so much reduced that AROT becomes predominant over airborne spacing. In this later case, the (airborne in-trail spacing minima, AROT) couple is located on the other side of the AROT-Airborne Spacing Equity line. Consequently, the direction of capacity increase points towards decrease of arrival runway occupancy time.

With these operational conditions, and as per Equation 6-33, it can be further concluded that arrival capacity is perfectly inelastic with respect to arrival runway occupancy time. However, arrival capacity is negatively unitary elastic with respect to airborne in-trail spacing minima,

$$\begin{cases} \mathcal{E}_{\gamma_a}(\tau^{arot}) = 0 \\ \mathcal{E}_{\gamma_a}(\tau^{air}) = -1 \end{cases} \text{ at the operational point } (50.46;80.13).$$

7.1.5 Related Impact of Final Approach Speed and Distance-based Separation Minima

Based on the fleet homogeneity and traffic demand constancy assumptions, and based on data collected and reported in Table 5-5, the weighted average speed on final approach is 139.8 kts, whilst the weighted average distance-based airborne separation minima is 3.1099 NM. Based on these two parameters, Equation 4-19 enables us to calculate a weighted average time-based airborne separation minimum of 80.07". It is to be noted that, in this process, the fleet homogeneity assumption requires us to calculate all the weighted averages at the source in order to get rid of addressing further various aircraft classes. It is however to be noted also, that dealing with fleet heterogeneity led to a weighted average time-based airborne separation minima of 80.13". This can therefore be concluded that the fleet homogeneity assumption results in an accuracy error of about 0.7% in this specific case. Whilst keeping this magnitude of order of possible error in mind, the fleet homogeneity assumption will be maintained in this specific case study for the purpose of clarity only.

As analysed in Section 7.1.4, the weighted average arrival runway occupancy time is 50.46", which is smaller than the average time-based airborne separation minima. Arrival runway occupancy will therefore remain beyond the scope of the analysis in this Section, and we will focus on approach speed and distance-based airborne separation minima only.

Based on Equation 6-36, arrival capacity resulting from the previous calculations is 44.96 arrivals/hour.

Further to the analysis of the inputs used (see Sections 5.3.2.1 and 5.3.2.2), the approach speed can vary between 125 kts for light aircraft up to 146 kts for heavy jets. As far as distance-based separation minima are concerned, they range between 3NM for minimum radar separation up to 6 NM between (medium-)heavy jets and following light aircraft. To gain enough flexibility, consider an interval for distance-based separation minima ranging from 2.5 to 6 NM. Figure 7-4 represents the 3-D functional relationship between arrival capacity, speed on final approach and distance-based separation minima. In this figure, it is not possible to go below a step of 0.5 in the parameters due to MatLab software graphical limitations, and therefore the operational point (3.1099; 139.8; 44.96) could not be located with great accuracy. The closest approximation based on high-accuracy computational calculations can however be visualised with an arrow.

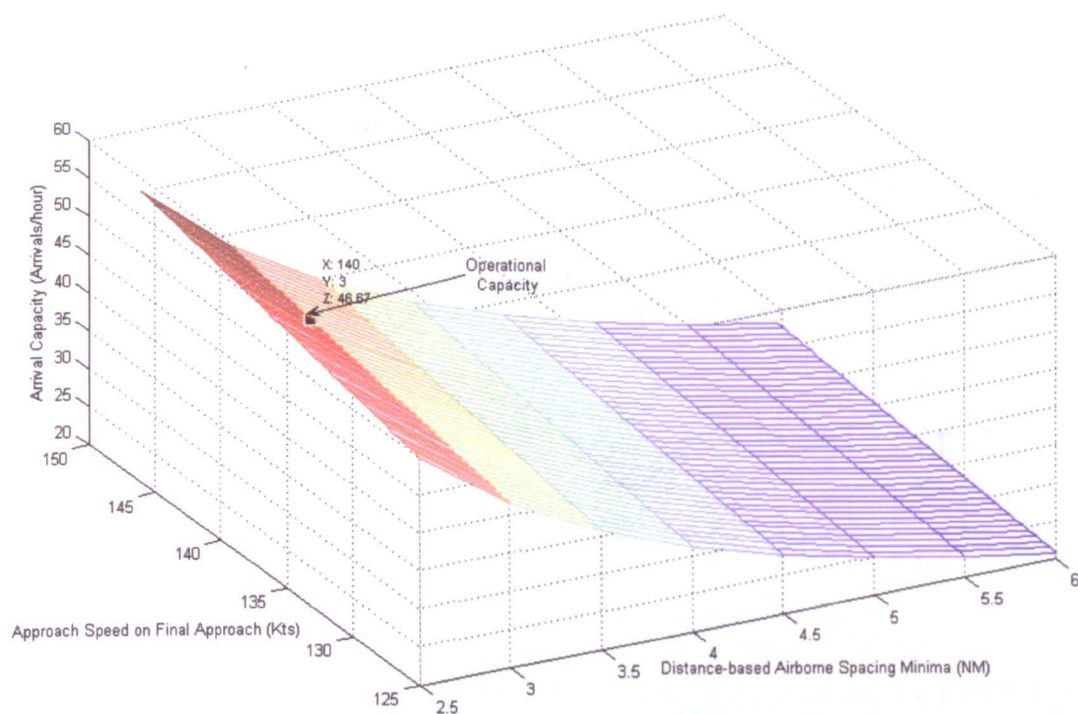


Figure 7-4 – Case Study - Combined Impact of Final Approach Speed and Distance-based Separation Minima on Capacity

Based on the formulation of the arrival capacity dynamics with respect to arrival runway occupancy time, distance-based airborne in-trail spacing minima and final approach speed in Equation 6-38, the arrival capacity dynamics at the operational point is represented by the vector:

$$\overline{\delta_{\gamma_a}(\tau^{arot}, \delta_{aa}^{air}, v)} = (0; -14.4571; 0.3216)$$

This result can be interpreted as follows. Any increase (decrease) of distance-based airborne in-trail spacing minima by 1 NM entails a capacity decrease (increase) of 14.5 arrivals/hour. On the other hand, any increase (decrease) of approach speed on final approach by 1 kt entails a capacity increase (decrease) of 0.3 arrivals/hour.

The gradient representation of the arrival capacity dynamics with respect to both speed on final approach and distance-based airborne separation minima is represented in Figure 7-5.

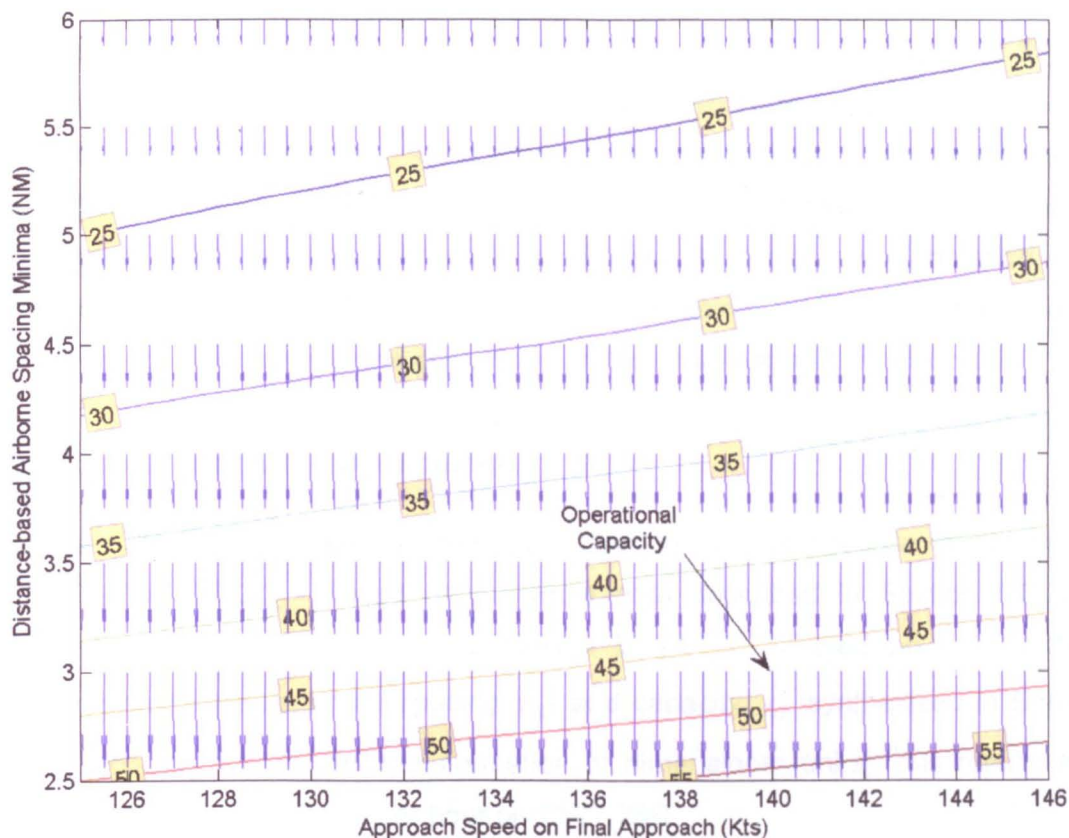


Figure 7-5 – Case Study – Gradient Representation of Arrival Capacity Dynamics w.r.t. Final Approach Speed and Distance-based Separation Minima on Capacity

The previous calculation of capacity dynamics at the operational point could make airport planners believe that arrival capacity is more sensitive to distance-based airborne separation than to speed on final approach. Others will argue that it is easier for speed to fluctuate by 1 kt than distance-based separation to change by 1 NM. This debate, however, should not be a key issue. It has to be borne in mind that this discrepancy between the orders of magnitude is apparent only, and due to the use of different units. Indeed, according to Equation 6-39 and Equation 6-40, the capacity elasticities with respect to approach speed and distance-based airborne separation are equal, although opposite: an increase of distance-based airborne separation by 1% entails an arrival capacity decrease of 1%; whilst an increase of speed on final approach by 1% entails an arrival capacity increase of 1%.

7.2 Departure Capacity

Whilst referring to Figure 6-4, it can be observed that the departure capacity branch of the runway capacity influence diagram is similar to the arrival capacity branch up to its 3rd level. Consequently, it is also observed that the equations of departure capacity dynamics and elasticities synthesised in Section 6.3.4 are similar to the equations defining arrival capacity dynamics and elasticities, reported in Section 6.3.3. Therefore, the case study for departure capacity dynamics is kept to the minimum in this Section, to avoid over-elaboration. Only two cases are reported: the impact of inter-departure spacing, and the related impact of departure runway occupancy time and airborne inter-departure separation minima.

7.2.1 Impact of Inter-departure Spacing

The departure capacity model was synthesized in Section 4.3.2 and a case study of it was reported in Section 5.3.2.2. Based on the input data described in Section 5.3.2, the weighted average inter-departure spacing minima is 74.53". Based on the functional relationship between inter-departure spacing τ_{dd} and capacity γ_d synthesized in Equation 6-46, and by applying the correct transformation of dimensions (units), this results in an arrival capacity of 48.30 departures per hour on RWY 25R.

The departure capacity dynamics with respect to inter-departure spacing at the operational point (74.53;48.30) can be calculated using Equation 6-47, and results in -0.6481 departures/hour/sec. Any marginal fluctuation of inter-departure spacing by 1" therefore leads to a negative change in capacity of 0.6481 departures/hour.

Equation 6-61 enables us to calculate a departure capacity stability factor equal to

$\frac{1}{0.6481} = 1.5430$ departures/hour/sec. At this stage, it can already be concluded that,

although outbound operations are performing better than inbound operations, departure capacity is slightly less stable than arrival capacity, which was characterised by a stability factor of 1.7835.

As per Equation 6-48, the inter-departure spacing elasticity of capacity is negatively unitary. In other words, any marginal fluctuation of inter-departure spacing by 1% results in a fluctuation in capacity of -1%.

The top subplot of Figure 7-6 shows the functional relationship between inter-departure spacing minima and departure capacity, over the inter-departure spacing interval [30";180"], whilst the middle subplot represents the fluctuation of departure capacity dynamics with respect to inter-departure spacing. Finally, the bottom subplot represents the inter-departure elasticity of departure capacity over the same inter-departure spacing interval. As concluded in Section 6.3.4.1, Figure 7-6 shows that departure capacity is more subject to change for low values of inter-departure spacing than high values, for the same marginal fluctuation of inter-departure spacing.

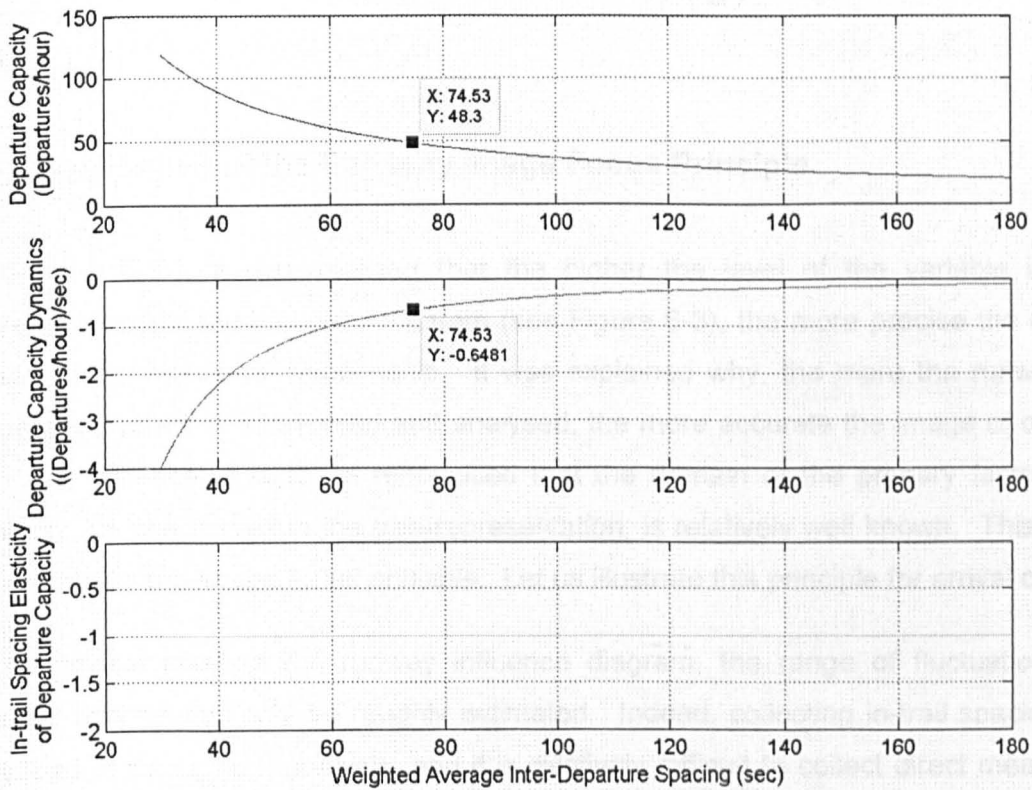


Figure 7-6 – RWY 25L - Impact of Inter-departure Spacing on Departure Capacity over the Interval [30";180"]

7.2.2 Related Impact of Departure Runway Occupancy Time and Airborne Inter-departure Separation Minima

In a similar way to the case study described in Section 7.1.4, the departure capacity dynamics with respect to both departure runway occupancy time and inter-departure spacing

minima is represented by the vector $(0; -0.65)$ at the operational point $(\tau^{drot}, \tau_{dd}^{air}) = (64.1721; 74.5339)$.

Departure capacity is not affected by departure runway occupancy time, as long as this factor does not become predominant over inter-departure separation minima.

With these operational conditions, and as per Equation 6-52 and Equation 6-53, it can be further concluded that departure capacity is perfectly inelastic with respect to departure runway occupancy time. However, departure capacity is negatively unitary elastic with

respect to inter-departure spacing minima.
$$\begin{cases} \varepsilon_{\gamma_a}(\tau^{drot}) = 0 \\ \varepsilon_{\gamma_a}(\tau_{dd}^{air}) = -1 \end{cases}$$
 at the operational point $(64.1721; 74.5339)$.

7.3 Application of the Capacity Image Focus Principle

In Section 6.3.1, it was realised that the higher the level of the variable in the tree-representation of the influence diagram (see Figure 6-3), the more precise the domain and image of the functional relationship. It was explained why, the more the runway capacity influence diagram is scrutinised and analysed, the more accurate the image of capacity can be. For instance, it is to be recognised that the domain of the primary factors affecting capacity, i.e. the *leaves* in the tree-representation, is relatively well known. This principle is referred to as the *image focus principle*. Let us illustrate this principle for arrival capacity.

At the lowest level of the runway influence diagram, the range of fluctuation of in-trail spacing minima can only be roughly estimated. Indeed, collecting in-trail spacing data can only lead to throughput analysis, and it is relatively difficult to collect direct measures of in-trail spacing minima. A rough estimate of the range of fluctuation was assessed in Section 7.1.1, that is $[30"; 160"]$. It was also calculated in Section 7.1.1 that the corresponding fluctuation of arrival capacity remains within the interval $[120; 22.5]$, which can be summarised as

$$\gamma_a(\tau_{aa}) = 3600 / \tau_{aa} : [30;160] \rightarrow [120;22.5]$$

On closer inspection of the runway influence diagram, it appeared that AROT could fluctuate between 40" and 100", according to statistical analysis based on direct measures. At the second level of the case study, in Section 7.1.4, it was however impossible to draw any conclusions regarding the operational fluctuation of time-based airborne in-trail separation minima, because this latter parameter was not directly measured at Brussels Airport.

However, moving up the runway influence diagram, in Section 7.1.5, a statistical analysis of approach speed resulted in a fluctuation of this capacity disrupter within the interval [125;146], whilst distance-based airborne in-trail spacing could fluctuate between the minimum radar separation and the maximum wake vortex separation minimum, i.e. within the range [3;6].

At the top of the runway influence diagram, the interval in which the three major capacity disrupters that affect arrival capacity are known, based on statistical analysis of direct measures. Based on Equation 6-36, it can be concluded that arrival capacity fluctuates between 20.83 arrivals per hour, in the most unfavourable case of approach speed and airborne separation, up to 48.67 arrivals per hour in the best case of these disrupters. The more accurate capacity fluctuation range can be summarised as follows:

$$\gamma_a(\tau^{arot}, \delta_{aa}^{air}, v) : [40;100] \times [3;6] \times [125;146] \rightarrow [20.83;48.67]$$

The *image focus principle* therefore enables us to remove any assumption regarding the possible range of fluctuation of the various capacity disrupters. Although beyond the scope of this research, detailed statistical analysis could provide the full probability function of capacity.

7.4 The Airport Planning Compass

The factor-based taxonomy approach, illustrated in Figure 2-2, represented a pragmatic approach to define capacity in relation to the factors that could affect it. Figure 2-4 illustrated the relationship between capacity and its disrupters, but only vaguely. Later, the capacity influence diagram, described in Section 6.3.1 and illustrated in Figure 6-3 and Figure 6-4, provided additional information on the complex relationship between the various capacity

disrupters, and enabled this relationship to be organised based on the degree of influence of these disrupters on capacity.

At Brussels Airport, but also at many other airports in Europe, it is experienced that planners can qualify and sometimes quantify the impact that various factors can have on capacity, but most often independently from each other and without any kind of hierarchy or gradation between these factors. This knowledge most often results from sensitivity analyses on the influencing factors performed independently from each other. On the other side, when airport planners perform "what-if" analyses, they get a global impact of several factors on capacity, without being able to identify the major and real causes of this impact. Thus, airport planners usually miss the dependency that might exist between the influencing factors considered together, and meet some difficulties in identifying which of these factors is the most affecting for given operational conditions. The need for a decision support tool is often identified, in order to better classify the various affecting factors by order of quantified influence. This assistance tool to decision-making would aim at putting the quantified impact of these various factors, within the context of their intrinsic relationship with capacity.

In this section, it is proposed to provide airport planners and decision-makers with a high-level 'strategic view' regarding runway capacity and the magnitude of its potential fluctuations. This global picture is illustrated by the development of a 'proof of concept' decision-support tool, the '*airport planning compass*'. As a further step of the capacity influence diagram, the airport planning compass enables the real impact of various capacity disrupters to be quantified through the use of the two concepts of capacity dynamics and capacity elasticities. The airport planning compass contributes to raising awareness of the major airport actors concerning capacity dynamics, whilst assisting them in identifying better the direction of potential change, and therefore investment. This tool will be illustrated in this Section for arrival capacity, and will enable the results from the case studies (Chapter 5 and Section 7.1) to be summarised in a graphical way.

As illustrated in Figure 7-7, the airport planning compass is composed of a quantified influence diagram, in which each box contains the following information:

- identification of the capacity disrupter;
- its absolute value;

- the capacity dynamics value with respect to this capacity disrupter, which provides airport planners with the instantaneous rate of capacity change for any unitary change of this disrupter;
- the capacity elasticity value with respect to this capacity disrupter, which provides the percentage of capacity change for a one percent change of this disrupter.

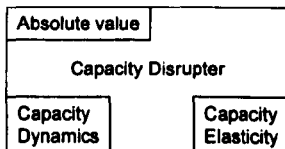


Figure 7-7 – Airport Planning Compass Component

Figure 7-8 represents the airport planning compass diagram for the case study of Brussels National Airport described in Section 7.1. The arrival capacity of 44.93 arrivals/hour is directly dependent on the weighted average in-trail spacing time of 80.13". In Section 7.1.1, the calculation of the capacity dynamics resulted in -0.5607 arrivals/hour/sec at the operational point (80.13;44.93), whilst the in-trail elasticity of capacity was negatively unitary. Breaking up the weighted average in-trail spacing impact further in Section 7.1.4 enabled us to conclude that capacity dynamics was exclusively caused by airborne in-trail spacing minima as long as this factor is predominant over arrival runway occupancy time (AROT). This *exclusive predominance* of one of these two factors over the other was illustrated in Figure 7-3 by the AROT-Airborne Spacing Equity line, and is represented by the switch *max* in Figure 7-8. The airport planning compass indicates that potential capacity change is in the direction of airborne in-trail spacing minima. The cause of possible capacity change was further analysed, in Section 7.1.5, with the impact of final approach speed and distance-based in-trail spacing. It was shown that any change in one of these two capacity disrupters entails a change in capacity, as indicated in Figure 7-8.

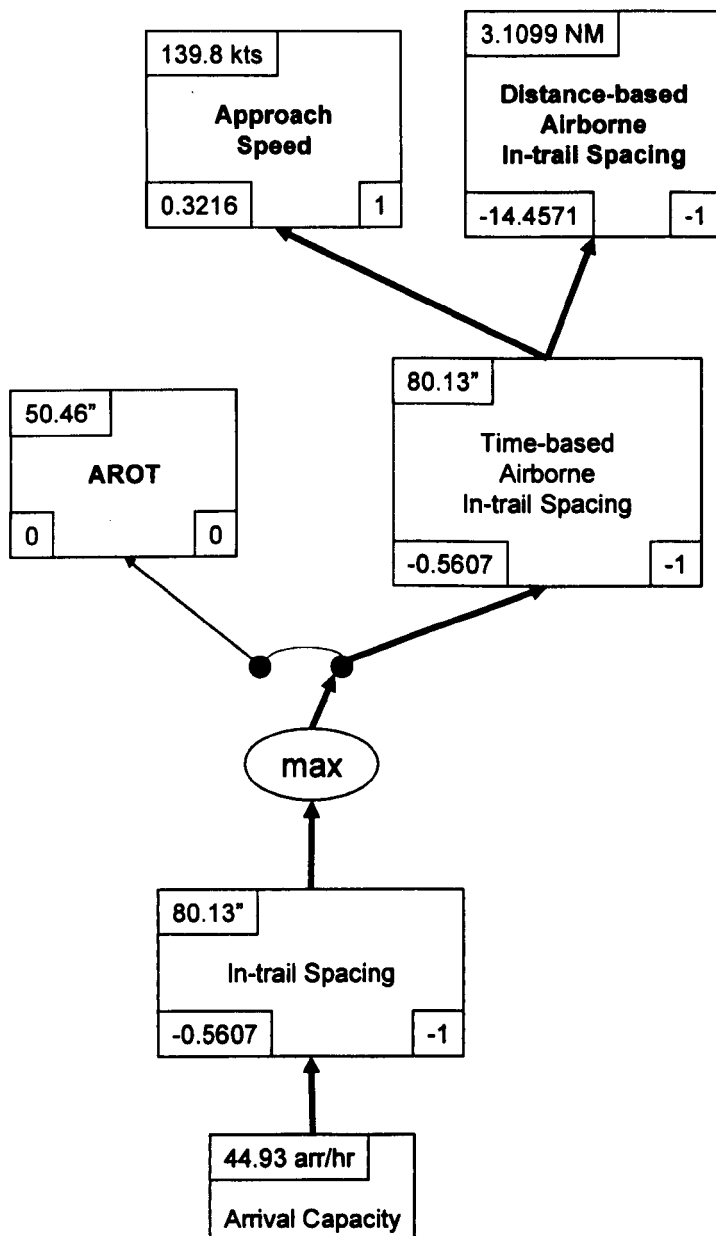


Figure 7-8– Airport Planning Compass Representation of Arrival Capacity Dynamics

Should airport planners and/or operators aim at changing capacity (either increasing it for capacity enhancement purposes, or decreasing it in order to gain capacity stability), they need to act on parameters under their control. For instance, it is relatively difficult, say impossible, to control directly time-based in-trail spacing minima because in-trail spacing is commonly distance-based. However, AROT, approach speed and distance-based separation minima are three capacity disrupters which airport operators can control, with relative ease. The *controllable* capacity disrupters are usually, but not necessarily, independent variables, and represent the leaves of the airport planning compass; they are

represented in bold in Figure 7-8. In summary, the airport planning compass indicates to airport planners and operators that, in order to gain 1 percent of capacity, they have to choose between increasing final approach speed by 1%, decrease distance-based in-trail spacing by 1%, or a combination of both for a total percentage change of 1%. These *directions for change* are represented as the bold arrows in Figure 7-8. The airport planning compass also indicates that AROT has absolutely no impact for the operational conditions under consideration in this case study.

The airport planning compass is all the more beneficial when there is a high number of capacity disrupters, especially when the fleet homogeneity assumption is relaxed. Clustering aircraft performance and operations entails a high combination of possible sequences: for instance, the 5 aircraft classes used in this case study (L, MT, MJ, MH and H) generate 25 possible approach sequences. This makes the presentation of the calculation relatively complex: four matrices were required in Section 7.1.3 for that purpose. The airport planning compass enables the results to be summarised in a simple global picture, as illustrated in Figure 7-9. In this figure, the in-trail spacing is split per possible approach sequence. The representation shows which sequence (MJ-MJ in this specific case) returns the highest capacity change for the same marginal fluctuation of in-trail spacing of all the possible sequences.

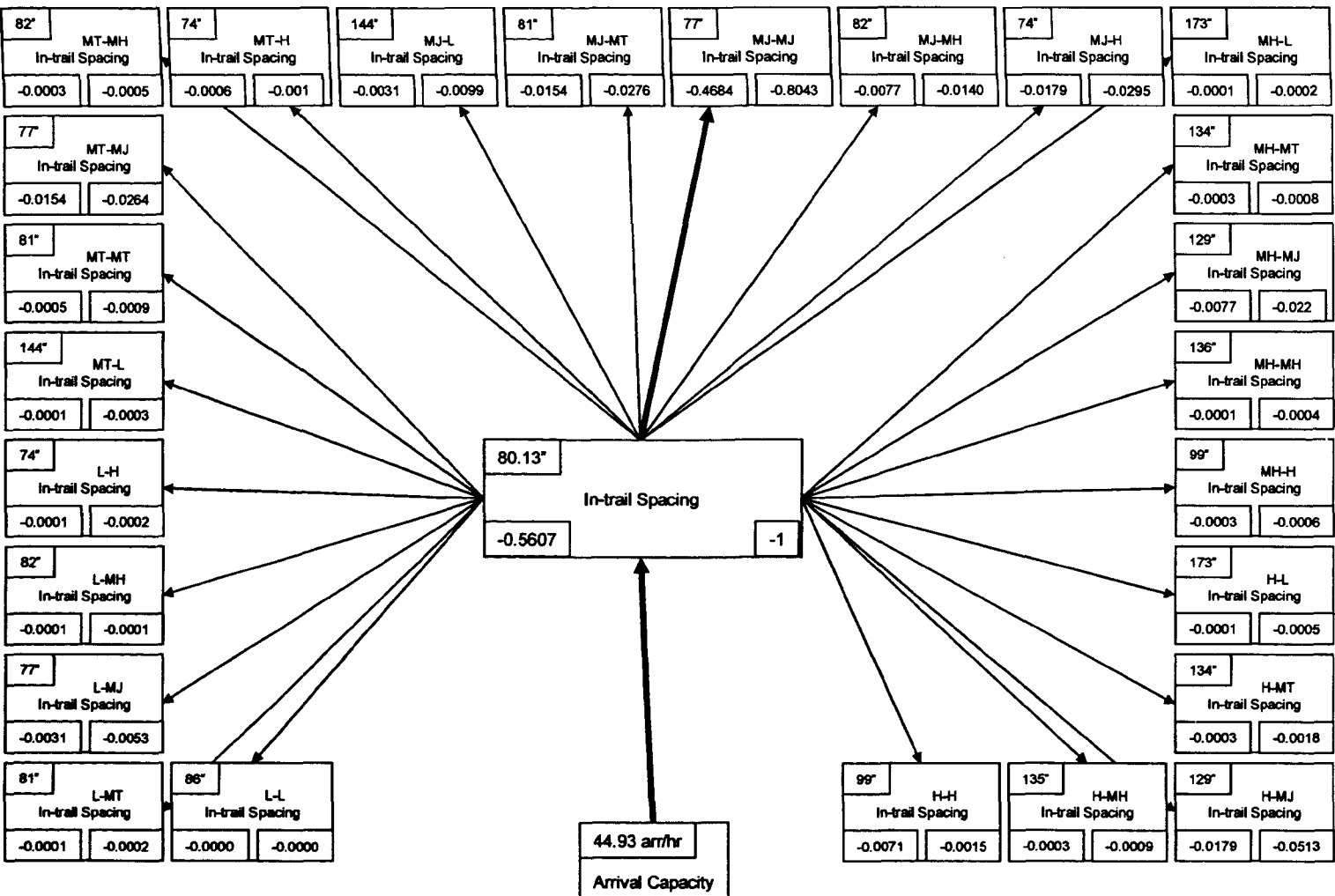


Figure 7-9— Planning Compass Representation of Arrival Capacity Dynamics, with the Relaxation of the Fleet Homogeneity Assumption

Based on this information, Figure 7-10 shows how to obtain the marginal fluctuation of the MJ-MJ in-trail spacing. Although the calculation of the capacity dynamics and elasticities with respect to AROT, approach speed and distance-based airborne in-trail spacing has not been undertaken because of the fleet homogeneity assumption in Section 7.1, it is clear that there are two controllable disrupters on which planners and operators can act: medium-jets approach speed, and distance-based airborne separation between successive medium-jets, which is further dependent on radar separation according to Equation 4-15.

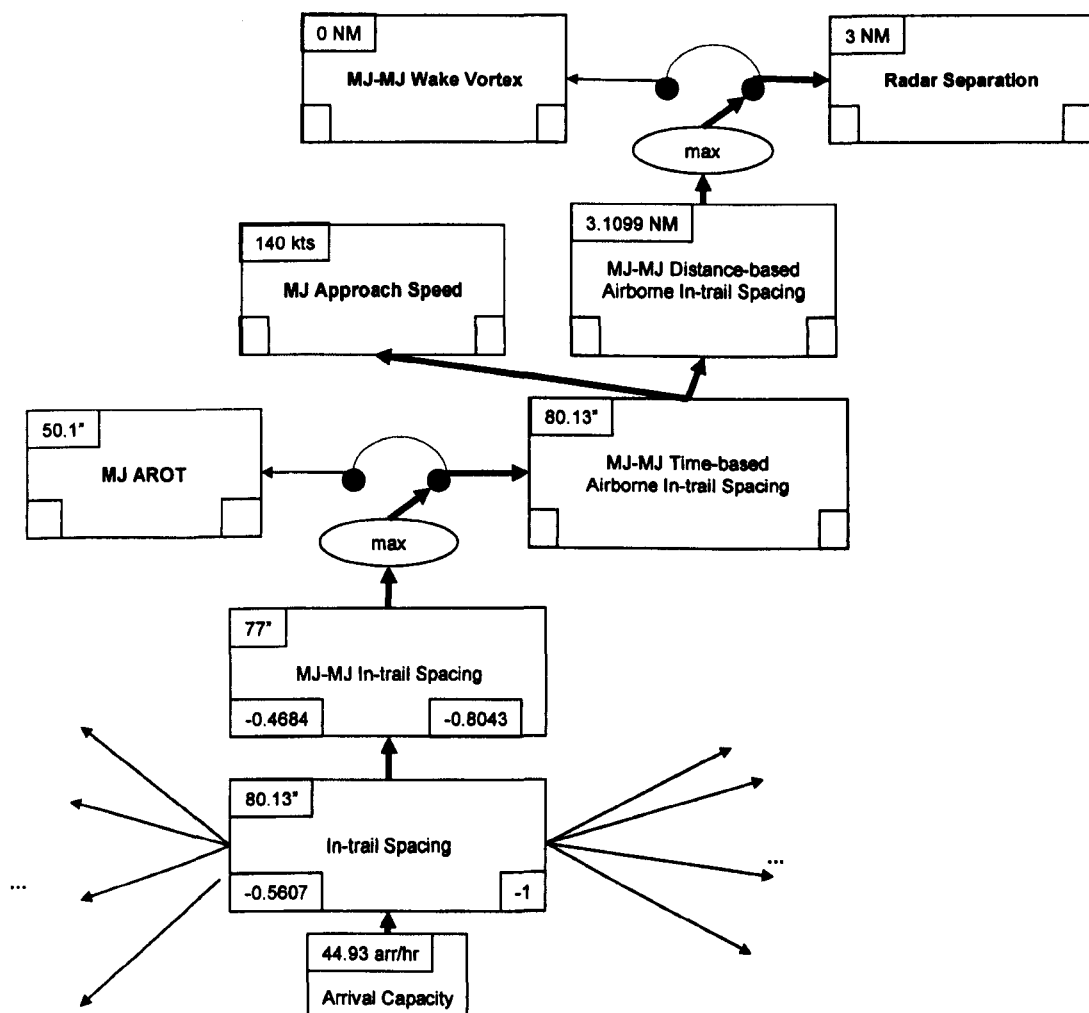


Figure 7-10– Extending the Airport Planning Compass for Arrival Capacity Dynamics

In conclusion, the airport planning compass application takes advantage of the synergy between and complementary nature of the two concepts of capacity dynamics and capacity elasticities. With additional development beyond the 'proof of concept' stage reported here, this tool could further assist and guide airport planners and managers in their process of capacity enhancement, as well as in the prioritisation of the different factors that affect capacity based on their real impact, i.e. the potential capacity enablers. The airport planning compass provides that high-level 'strategic view' in terms of both tactical and strategic airport planning.

Chapter 8 - Conclusion and Opportunities for Further Research

8.1 Research Conclusion

Air transport in Europe is forecast to grow from 9.1 million IFR flights in 2005 to 18 million IFR flights by 2020. Compared with 35 in 2005, 60 European airports will be congested by 2020, and the top 20 airports will be saturated between 8 and 10 hours a day. It was in this context that this research has proposed introducing the new concept of capacity dynamics in order to enhance capacity management and airport planning efficiency. The purpose of this research was twofold. The first and key objective was to define and formulate the three concepts of capacity dynamics, capacity elasticities and capacity stability. Based on the appropriate formulation of runway capacity, the impact of all the factors that affect runway capacity was analytically synthesized. These three concepts enabled us to quantify which conditions, and to what extent, various factors may affect airside capacity. The second objective consisted of demonstrating the operational usability of these three concepts through their application in a real case study on a representative European airport, Brussels National Airport. The added value of these three concepts was shown with a decision-making assistance application in support of strategic and tactical planning: the *airport planning compass*.

There are so many different definitions of capacity that airport planners and modellers often do not know which way to turn with regards to the use of terminology in a consistent way. These various definitions were reviewed in depth. It was concluded that a number of definitions give place to possible misunderstandings or misinterpretations caused by poor perception. It was also recognised that the choice of a given definition of the same terminology originates sometimes from the intention to reflect the personal interest of some stakeholders. In order to mitigate that risk of misunderstanding or misinterpretation, a more pragmatic definition, based on capacity disrupters, was developed: the factor-based definition of capacity.

One key preliminary task performed in this research was to review the literature on runway system capacity modelling. In the literature, it was discovered that airport airside modelling commonly addresses single runway operations from the capacity assessment perspective only. Based on the state-of-the-art of literature, it can be clearly concluded that the problems of capacity dynamics, capacity elasticities and stability have not been addressed. Further

consultation and coordination with the Scientific Community confirmed that the proposed concepts have not been investigated.

The various factors that affect runway system capacity were reviewed, and a relationship diagram was elaborated. Synthesising runway capacity enabled key issues to be identified that are not always fully considered, even mastered, by airport modellers. First, based on the explanation of the throughput cumulative function, the peak-sustainability paradox addressed the sensitive choice of appropriate time intervals within a selected traffic sample. On the one hand, the average flow over a long period of time removes the surges which one may wish to describe and analyse; on the other, too short time intervals might represent outlying peaks in traffic that are statistically not representative. Second, the confusion by modellers between throughput and capacity too often leads them to the conclusion that fast-time simulation provides useful capacity figures. It was explained why mimicking airport operations can at best result in throughput, whilst capacity analysis requires other modelling techniques, analytical modelling being one of them.

Synthesising runway capacity enabled the functional dependency between the process of arrivals and departures to be analysed from a pure mathematical perspective. This enabled us to show that the capacity envelope, represented by a piece-wise convex curve, can be considered as a strictly decreasing monotonic bijection over a restricted domain corresponding to mixed mode of operations. Whilst reducing the equation of the capacity envelope, this conclusion is of major importance in terms of research into the capacity allocation problem.

The runway capacity model was applied as a first case study related to a representative co-ordinated European airport: Brussels National Airport. This airport was chosen because it *a priori* fulfilled the key selection criteria for case study appropriateness. Although detailed data were missing to make the case study complete, the best attempt was made with the level of information available. Adequate airport telemetry could provide the level of detail required to fully validate the capacity dynamics concepts; however, airport telemetry does not exist yet in a systematic way at European airports. It is to be recognised that, even if Brussels Airport does not constitute an ideal case, no other airport was found to be better.

Real operational data were collected and analysed, with the particular and major concern of reflecting reality as close as possible. A thorough throughput analysis addressed the critical issue of choosing an appropriate traffic sample, and strengthened the peak-sustainability paradox. This case study showed that the arrival capacity is usually more critical than

departure capacity, because of the greater uncertainty intrinsically linked to approaches compared to departures. That is also the reason why the mixed mode of operations with pre-emptive priority to departures is very unlikely to happen in real operations, and can therefore be better considered as an academic case. It was also shown, in this specific case study, why arrival runway occupancy time is less critical than in-trail airborne separation with respect to arrival capacity, although arrival runway occupancy time might affect alternating capacity as well.

The results of the first case study were tested using two different methodologies. The first validation methodology was based on an empirical analysis of the realised handling capability of the airport, over a time horizon that is sufficiently large to be able to deduce statistically reliable conclusions, whilst the second method is based on operational expert judgement and analysis sharing with local airport operators and ATS experts. The empirical data analysis revealed two major difficulties. First, the choice of appropriate outliers' rejection criteria is quite critical. These criteria enable the extreme and not representative observed data in the statistical sample to be rejected. Second, the choice of the appropriate percentile in the empirical analysis is critical as it depends on the verification of the close-to-saturation assumption. Despite these difficulties, there was a relatively good correspondence between the 99.5th percentile of maximum realised handling capability and calculated capacity, with a close-to-saturation condition represented by a capability/capacity ratio ranging from 80% to 91%. This empirical analysis was complemented by an operational validation with airport operators and ATS experts. Several meetings were organised with the Vice-President Strategy at Brussels Airport and ATS experts, in order to present and share the analysis, and to discuss the results of the model. The two validation methodologies confirmed the validity of the results of this specific case study.

The validation of the runway capacity model could then be used as a robust basis for the development of the new concepts of capacity dynamics. The relationship diagram previously defined was further developed into a runway capacity influence diagram. This runway capacity influence diagram was used as the basis for a rigorous methodology set up for the purpose of synthesising the concepts of capacity dynamics, capacity elasticities and capacity stability.

The concepts of capacity dynamics were defined in order to contribute to and favour the *a priori* understanding of the system to be modelled, in opposition to the *a posteriori* analysis of modelling "trials". These concepts also assist airport planners in better predicting and

quantifying system behaviour than their intuition alone could permit. Capacity dynamics provides a performance indication about how quickly capacity is able to change at any specific point, further to fluctuation of the capacity disrupters. Capacity dynamics quantifies the instantaneous rate of capacity change, and provides the direction in which capacity changes most quickly within the n-dimensional capacity space. It also provides a means for smooth implementation of capacity enhancement plans.

The concept of capacity elasticities measures the percentage change in capacity with respect to percentage change of any of the capacity disrupters. This indication was shown to be valuable for airport planners as it reflects capacity responsiveness with respect to fluctuation of its disrupters. Because they are relative, the elasticities of capacity release pressure and therefore save costs on data collection and calibration of baseline scenarios.

Based on the analysis on these concepts, eight key conclusions may be drawn. First, any division of in-trail (inter-departure) spacing by a factor of 2 multiplies the magnitude of the impact on arrival (departure) capacity change by a factor of 4, for the same marginal fluctuation of in-trail (inter-departure) spacing, and vice-versa.

Second, arrival capacity is negatively unitary elastic with respect to in-trail spacing, i.e. any percent increase (decrease) of in-trail spacing has an impact on arrival capacity equal to one percent decrease (increase). The same phenomenon was demonstrated for departure capacity.

Third, with a heterogeneous fleet environment, the fluctuation of in-trail spacing for a given sequence of approaches contributes on a pro rata basis to the global arrival capacity dynamics, i.e. proportionally to the probability that this sequence appears. The same phenomenon is also valid for departure capacity with respect to a heterogeneous outbound fleet.

Fourth, any decrease of arrival (departure) runway occupancy time below the level of airborne in-trail (inter-departure) spacing does not impact on arrival (departure) capacity, and vice versa, if in-trail spacing is smaller than arrival runway occupancy. Capacity was demonstrated to be negatively unitary elastic with respect to the predominant of these two factors, but perfectly inelastic with respect to the other. Consequently, any investment in a new runway exit was shown to be irrelevant and unprofitable in good weather conditions, for a runway used for arrivals only, as soon as runway occupancy related to the use of this new runway exit becomes smaller than airborne in-trail spacing. In a similar way, the conditional

take-off clearance procedure is not beneficial from a departure capacity perspective as long as inter-departure spacing is not smaller than departure runway occupancy time.

Fifth, arrival capacity is perfectly inelastic with respect to both distance-based in-trail spacing minima and final approach speed when arrival runway occupancy is predominant over time-based in-trail spacing minima. However, when time-based in-trail spacing is greater than arrival runway occupancy, arrival capacity is negatively unitary elastic with respect to distance-based in-trail spacing minima and positively unitary elastic with respect to final approach speed.

Sixth, arrival capacity is also negatively unitary elastic with respect to wake vortex separation minima only when this latter factor is predominant over radar separation and arrival runway occupancy time. In any other case, wake vortex does not affect arrival capacity.

Seventh, and in a similar way, arrival capacity is negatively unitary elastic with respect to radar separation minima only when this latter factor is predominant over wake vortex separation and arrival runway occupancy time. This happens at most of airports which are not equipped with on-site radar, which generally results in in-trail separation minima greater than 5 NM.

Last but not least, the capacity stability concept developed has clearly demonstrated that, the higher an airport is performing from a capacity perspective, the more sensitive its capacity is to potential fluctuation of some of its disrupters, and therefore the less stable it becomes. This capacity/stability paradox definitely raises serious questions about maximizing capacity for ever, and questions the ultimate goal of capacity enhancement. Legitimately, it also raises the question whether investment at secondary airports would not be more worth than similar investment at major airports.

The three concepts of capacity dynamics, elasticities and stability were demonstrated to be useful in support of this capacity/stability paradox, because they rigorously quantify the impact of capacity degradation. They can assist in better quantifying the risk of potential capacity fluctuation and drafting related mitigation plans, in the scope of both strategic and tactical airport planning. Such mitigation plans should be an integral part of any effective airport plan in order to better predict the response to give to potential capacity degradation when those events occur.

The three concepts of capacity dynamics, elasticities of capacity and capacity stability were illustrated through a second case study, based on the same operational data at Brussels National Airport. The *airport planning compass* enabled the different factors that affect capacity to be prioritised, based on their real impact. This decision-making support tool can assist and guide airport planners and managers in their process of capacity enhancement, as well as in the prioritisation of potential capacity enablers in the scope of both tactical and strategic airport planning.

In conclusion, the traditional process of capacity analysis has been shown to be insufficient. Some planners too often rely on their intuition regarding the potential impact of some factors on capacity. The complementary concepts of capacity dynamics, elasticities and stability provide a robust formulation of the dynamic impact of these factors and, by that way, contribute to substitute scientific argumentation for intuition. The three concepts of capacity dynamics should be quantified and fully analysed, and be an integral part of any capacity enhancement plan.

8.2 Self-evaluation of the Research

This Section aims to provide a self-evaluation of the process adopted during this research and to identify its strengths and weaknesses. Although such self-criticism is intrinsically subjective, it attempts to identify some traps that could be avoided in further research in this area, based on the lessons learnt.

Evaluation of the Research Process

The desire of undertaking research, and a PhD in particular, does not come by accident; this desire usually emerges during university education, if not earlier. At that moment, two options often appear: either to start research directly after graduation, or to wait to gain valuable professional experience with the risk of losing some part of the academic background. Ideally, research would require full time attention. However, and for practical reasons, this research was undertaken in parallel with professional activities. The major disadvantage of this option is that the mix with professional activities represents a clear constraint, which is detrimental to the speed at which the first results appear. It consequently requires all the more motivation to lead research to a successful end. However, and predominantly, the key benefit of this option is operational reusability and applicability.

Expected Contribution

As noted in Section 1.1, the cost of cutting 5 minutes off 50% of flight schedules is estimated at some €1 billion per annum in better use of airline and airport resources. Beyond operational improvements such as, for instance, system-wide information management and collaborative decision-making, it is clear that the scientific community needs to pursue its support of airport modelling and consider unpredictability in air transport operations. Capacity modelling has been addressed by scientists, but thus far not capacity dynamics, and this makes the operational world think that the only way to mitigate airport delay is through capacity enhancement.

It is strongly believed that part of the cost of unpredictability can be recovered by enhancing capacity management efficiency, which requires a better knowledge of the capacity fluctuation mechanism. A rigorous analysis of capacity fluctuation can only emerge from the scientific community. This research only proposes one possible approach to solving the capacity dynamics problem. It is however hopeful that this approach can contribute to improving capacity management efficiency, and can lead to a better use of airport capacity.

The major contribution of this research also lies in the conclusions reported in Section 8.1, which might have been intuitively obvious to a few airport planners but which has never quantified *a priori*. The major objective of airport capacity modelling thus far has been focused on capacity assessment and *a posteriori* analysis through 'what-if' scenarios and sensitivity analysis based on modellers'/planners' intuition of how capacity could fluctuate. Through this *a priori* analysis of capacity fluctuation mechanisms, this research provides a new dimension to airport capacity planning. In addition, the conclusions on capacity stability bring additional arguments in the debate of investing at major or regional airports.

In the scope of the single European sky air traffic management research and modernization programme (SESAR), the European Commission proposed to set up a pan-European observatory of airport capacity. Although beyond the scope of the present research, the concept of capacity dynamics can be applied to other airports and contribute to the improvement of the pan-European planning process of airports.

Lessons learnt

It can be concluded that the methodology used in the scope of this research, as illustrated in Figure 1-2 and described in Section 1.3, was useful and represented a valuable support and

guidance. Some difficulties however appeared and had to be managed, especially regarding the identification of the problem (Figure 1-2, Box 1), validation of the case study (Box 5 and 9), as well as reporting (Box 10).

The identification of the problem is undoubtedly a very critical phase. At the beginning of this research, the scope was identified as being the full airport airside, including the runway system, taxiways and apron/stands. For that purpose, research was undertaken on ground traffic efficiency modelling, and the correspondence with urban transport modelling was investigated. After having attended and studied a course on urban transportation networks based on Sheffi's (1985) system-user equilibrium analysis with mathematical programming methods, it was concluded that urban transport modelling could bring limited value to the scope of ground traffic efficiency modelling. In addition, it had to be recognised that, for such a 'proof of concept' approach to succeed, in-depth research would be more beneficial. It was therefore decided to focus on the airport airside component that is the most critical, i.e. the runway.

Once the research target is identified, it is also necessary to stay focussed and resist any temptation to diverge from it. There are some desert-like mirages that can make researchers want to turn around and take a different path. For instance, at one stage of this research, it was believed that appropriate curve fitting and parameterization of the capacity envelope would help in formulating stability. Although capacity parameterization might represent an elegant alternative to more complex algorithms used in the scope of capacity allocation, it was abandoned as far as capacity dynamics is concerned.

The operational validation of the case studies was another major difficulty, for three reasons: the conflicts of interest of the various actors involved, data availability, and the choice of one or several appropriate validation methodologies.

The major risk of the operational validation of the first case study of Brussels National Airport was the review of the results by the operational experts from a socio-political perspective rather than on a pure operational basis. Indeed, this operational validation involved several actors with their own objectives, often subject to conflicts of interests. In addition, the airport actors are often afraid that the results will be used for the purpose of performance measurement.

The second case study had to face the lack of data availability. Airports usually collect data on purpose, especially when a capacity assessment is initiated. The controllable capacity

disrupters (e.g. AROT, approach speed, etc) are not systematically measured, and this information was not available at Brussels National Airport. It was therefore impossible to fully validate the capacity dynamics concepts from an operational point of view. Mainly for that reason, the validation was slightly constrained and treated on the overall outcomes of the analyses and not on intermediate calculations. With the implementation of advanced surface movement guidance and control system (A-SMGCS) and multi-lateration radars, it is hopeful that airport telemetry can be developed and data can be automatically measured if the need arises. Such data availability (including weather information) should be one of the major selection criteria for a test-bed airport in further research, in addition to adequacy of airport characteristics, access to airport information and support provision by operational experts.

Subject to data availability, historical data could be clustered according to operational conditions experienced at the airport. The same methodology could have been applied in order to provide capacity curves for the various sets of operational conditions that characterise the operations at the airport. This has not been undertaken in this research for two reasons: first, this research focuses on the development of a 'proof of concept' decision-support tool and methodology rather than on covering the full range of operations. It is clear that analysing the full range of operations would have been beneficial for the airport operators and is highly recommended for an operational capacity analysis. However, there would have been very little additional value from a research point of view and no enhancement of the methodology itself. Second, the data provided by the airport were not detailed enough and did not include any disaggregation per type of operation or airport states.

The choice of appropriate validation methodologies is primordial. The realised handling capability methodology, based on empirical distribution analysis, is a macroscopic airport assessment that, in essence, focuses at the airport level and not on any of its individual components. Because it is based on non-disaggregated airport airside throughput data, the output of the realised handling capability analysis does not enable the identification of the constraining airport component, i.e. runway system, taxiways, aprons, stands, terminal or landside. On the other side, analytical models, in particular the one synthesised in Chapter 4, are most often specific to one individual component. If the focus is on the runway system, airport modelling analysts should be warned that, because of the difference in scope between realised handling capability analysis and analytical modelling of runway system capacity, the results might substantially differ when the weakest and most constraining

airport component is not the one under investigation (e.g. the runway system in this research). It is realistic to believe that the constraining airport component can be known *a priori* because qualitative expert judgement is enough for that purpose. As far as this case study is concerned, it has been *a priori* known, based on expert judgement and operational experience, that the runway system was critical at Brussels National Airport, in particular in terms of departure capacity. In any further research, however, it should be checked that the component under investigation is the most critical one at the test-bed airport, otherwise other validation techniques should be used.

Finally, the decision to initiate and complete the report of the results stemming from research is a difficult step, because researchers are often dying to go further. In a personal conversation, Dr. Ir. Herman Neukermans (2007), Vice-President Strategy at Brussels International Airport Company, and Advisor Brussels Slot Coordination, stated the following frustrating paradox: *"You could go on for ever with a thesis; otherwise it would not be a thesis, would it? But at some stage, you need to recognise that making the point is essential."* The decision to stop this research for a short period was a difficult decision to make, but was essential because it enabled the results to be openly debated and confronted before continuing with it.

In the opening pages of this thesis, it was noted that research was all about rushing into a tunnel with a feeling of never-ending, but with the intense wish of seeing light again. It was added that, when daylight appeared again, the sun was shining more than ever. It is to be added here that, as soon as researchers reach the end of the tunnel, they are already looking towards further horizons; researchers are definitely explorers of the mind. Based on these considerations, opportunities for further research are identified in the next and final Section.

8.3 Opportunities for Further Research

During this research, various opportunities for further research were identified. Without being exhaustive, these opportunities are described in this section, and can be classified as follows:

- runway system capacity modelling, based on the review of literature in Chapters 3 and 4;

- case studies and validation, based on the exercises reported in Chapters 5 and 7; and finally,
- capacity dynamics, based on the conclusions in Chapters 6 and 7.

8.3.1 Further Development on Runway System Capacity Modelling

In 2nd-generation airport capacity models, the arrival/departure ratio is mostly addressed as a discrete variable, through the five following hypothetical conditions: departure only, mixed mode of operations with pre-emptive priority to departures, balanced arrival/departure, mixed mode of operations with pre-emptive priority to arrivals, and arrivals only. Any intermediate value between those five hypothetical conditions is obtained through extrapolation. Further research should be conducted in order to investigate traffic mix as a continuous variable. To do so, one research option is to extend the current analytical modelling technique to variable and combinatorial sequencing of flights, whilst mixing inbound and outbound flows of traffic. Curve fitting could then be used in order to ensure the continuum characteristics of the capacity envelope.

Some variables affecting capacity, like wind direction, wind speed, and planned number of arrivals and departures, can be quantified with relative accuracy. The combination of fuzzy modelling, as proposed by Netjasov (2004), and pure analytical modelling is therefore expected to increase capacity assessment accuracy.

Although most of the literature reviewed supports modelling development by relatively robust and validated numerical experiments and case studies, it is to be stressed that most of them focus on the single runway airport case. It is believed that there is still some potential to further develop multiple-runway system capacity modelling. No model currently exists either regarding multiple-airport systems. Further research could also be undertaken in order to extend the models to a multi-airport network, in order to complete the airport picture of a complete air traffic management (ATM) network.

8.3.2 Potential Enhancement of Validation Methodologies and Techniques

Concerning the case studies and validation methodology that were used, other potential improvements can be proposed.

As indicated in Section 5.4.1, the realised handling capability analysis can be assimilated to capacity if and only if the 'close-to-saturation' condition is met. For congested airports only, it is reasonable to assume that the historical peak data reflects the maximum operational capabilities and, hence, can be useful for capacity estimation. This condition is however not analytically defined. The quantile-based methodology used to identify close-to-saturation conditions was sufficiently adequate and acceptable for the purpose of this research. However, other methodologies to verify the close-to-saturation conditions might be more adequate for other case studies, and should be further investigated, providing that delay is clearly defined, as well as the *saturation thresholds*. For instance, significant delay records indicate that the airports operate close to, or at their operational limits. Subject to further research, the delay experienced by airports under certain operational conditions could represent a good indication that the 'close-to-saturation' assumption is verified for this same set of operational conditions. An alternative, and maybe complementary methodology, would consist of assuming that the close-to-saturation condition can be represented by a saturation factor, as suggested in Section 5.4.3.

The choice of a single case study in this research is based on the strategy to illustrate the capacity dynamics concepts from an operational perspective, and to demonstrate their beneficial contribution and added value to airport planning (e.g. the airport planning compass). For the purpose of concept formulation, a wider range of case studies would not be worthwhile. However, once demonstrated in depth for one airport, it would be worth analysing the concepts of capacity dynamics on a wider panel of European critical airports in order to gain a larger experience and cover different operational conditions.

8.3.3 Capacity Dynamics

Finally, because it is the major topic of this research, and because it has never been addressed before, capacity dynamics is the area in which the most important opportunities for research are identified.

The concepts of capacity dynamics, elasticities and stability were synthesized in Chapter 6 and illustrated through a case study in Chapter 7. For the purpose of clarity, the two assumptions of traffic demand constancy and fleet homogeneity were made. It was shown however that these assumptions could be relaxed, through the formulation of capacity dynamics and elasticities for a heterogeneous fleet mix. Relaxing completely these two assumptions undoubtedly constitutes promising further research, which would enable further

conclusions on variable traffic demand, variable traffic mix and heterogeneous fleet to be drawn. This further research could also support business cases related to capacity enhancement initiatives, by providing decision-makers with real quantification of the profitability related to such initiatives per type of aircraft. It will also enable us to quantify better the cumulative impact of some capacity disrupters. For instance, it was shown how approach speed on final approach can affect airborne in-trail spacing. However, this disrupter has also an impact on arrival runway occupancy time. To be complete, the research should consider the combined effect of approach speed before being able to make the right decision to be adopted on an operational basis.

It is recognised that delay grows exponentially with demand/capacity ratio. Nowadays, airport planners and operators intuitively mitigate the delay impact through consensus on an artificial acceptable level of delay. Another fundamental area of research is the correlation between the capacity dynamics concepts, as defined in this research, and the risk of delay growth. For those airports that are operated close to saturation and close to optimum capacity, the capacity dynamics concepts provide airport planners with an indication of the direction of the steepest slope. Should capacity be declared close to saturation, capacity dynamics provides an indication about how quickly capacity can decrease from that declared capacity, and consequently how quickly delay can grow. For those airports, it is likely that high negative capacity dynamics and small capacity stability are a forewarning sign of delay growth. Further research should be performed on the statistical correlation between capacity dynamics and delay, based on operational records at various saturated airports.

It was shown why high-performance airports are less stable than low-performance airports. The trade-off between capacity and stability is raised in this research as a major enabler to enhance the quality of airport planning. However, in order to optimise this trade-off, an acceptable level of capacity stability should be investigated, and synthesized as a function of the relative accuracy of the capacity disrupters. Indeed, roughly speaking, one cannot expect the output of a system to be more precise than the accuracy of its inputs. This raises the major concern that, beyond a lower stability, the capacity of a system cannot be enhanced indefinitely, and can only be increased up to the point at which capacity stability remains below the natural fluctuation of the disrupters of that system.

For most planning and operational purposes, capacity is used and declared as a single value determined for a given set of operational conditions assumed to be relatively stable during some given period. This research clearly demonstrated that capacity was not stable, due to

the possible fluctuation of its disrupters. It is clear nowadays that slot scheduling efficiency is not optimum because of a lack of specific guidelines, and because capacity declaration practices do not always consider the factors that are really sensitive. The practices for capacity declaration and slot scheduling should be revisited, and it is legitimate to question if capacity dynamics does not represent an appropriate indication of declared capacity robustness. The concept of slot scheduling quality management should be introduced, based on a predefined acceptable level of capacity stability, and based on the accuracy of the disrupters under control.

Finally, the capacity dynamics concepts were defined for runways only. Based on the same principles but after re-formulation of the concepts, it would be challenging to extend the domain of applicability, and to investigate and identify the value of these concepts in other domains within air transport (for instance, to the total airport system).

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Appendix A – Model Programming and Software Code

The model is best developed using the MATLAB software package (The MathWorks Inc., Natick, MA, USA). MATLAB is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numeric computation. MATLAB enables us to perform prototyping and design and program mathematical models faster than with traditional programming languages such as C, C++, and Fortran.

Software code transparency was a major concern during development. This source code is self-documented. Any critical command is commented as follows:

```
% This is a comment
```

All the procedures are also organised in various sections in order to clarify the algorithmic. Sections are represented by `%%`, for instance

```
% This is a new section within this function
```

```

function rwy_sys=RunRunSysCap(rwy_sys,display)

for i=1:rwy_sys.nb_rwys

    rwy_cap_calculation=RunRWYCap(rwy_sys.rwy{i},rwy_sys.cap_unit);

    rwy_sys.rwy{i}.out = rwy_cap_calculation;

end

switch (rwy_sys.nb_rwys)

    case 1

        rwy_sys.cap_env = cell2mat(rwy_sys.rwy{1}.out.capacity_envelope);

    case 2

        if ((findstr('ARRIVAL_ONLY',rwy_sys.rwy{1}.mode_ops)) &
(findstr('MIXED_MODE',rwy_sys.rwy{2}.mode_ops)))

            %

        elseif ((findstr('MIXED_MODE',rwy_sys.rwy{1}.mode_ops)) &
(findstr('ARRIVAL_ONLY',rwy_sys.rwy{2}.mode_ops)))

            cap_env1 = cell2mat(rwy_sys.rwy{1}.out.capacity_envelope);

            cap_env2 =
repmat([cell2mat(rwy_sys.rwy{2}.out.capacity_envelope)
0],size(cap_env1,1),1);

            rwy_sys.cap_env = [cap_env1(1,:);cap_env1 + cap_env2];

        elseif ((findstr('CLOSED',rwy_sys.rwy{1}.mode_ops)) &
(findstr('ARRIVAL_ONLY',rwy_sys.rwy{2}.mode_ops)))

            rwy_sys.cap_env =
cell2mat(rwy_sys.rwy{2}.out.capacity_envelope);

        else

            %

        end

```

```
end

X_Data = rwy_sys.cap_env(:,1);
Y_Data = rwy_sys.cap_env(:,2);

delta_value = 1e-10;

interpolation_unitary_step = 10;

[X_Data_Inter,Y_Data_Inter] =
interpolateLengthSegment(X_Data,Y_Data,delta_value,interpolation_unitary_step);

cap = X_Data_Inter + Y_Data_Inter;

pa = X_Data_Inter./(X_Data_Inter + Y_Data_Inter);

rwy_sys.pa_profile = [X_Data_Inter' Y_Data_Inter' cap' pa'];

pa2 = [0:0.01:1];

cap2=interp1(pa,cap,pa2);

rwy_sys.pa_profile_normalised = [(pa2.*cap2)' (cap2.*(1-pa2))' cap2'
pa2'];

if (display)

    displayRwySysCapEnvelope2D(rwy_sys.cap_env,rwy_sys.scenario_title);

    displayRwySysCapEnvelope3D(rwy_sys.cap_env,rwy_sys.scenario_title);

displayTrafficMixProfile(rwy_sys.pa_profile,rwy_sys.scenario_title);

%% Single Runway Capacity Calculation

function rwy=RunRWYCap(rwy,cap_unit)
```

```
% calculation of the various points of the capacity envelope
if findstr('ARRIVAL_ONLY',rwy.mode_ops)

    rwy=getArrCap(rwy,cap_unit);

    rwy.capacity_envelope = {rwy.cap_arr};

elseif findstr('DEPARTURE_ONLY',rwy.mode_ops)

    rwy=getDepCap(rwy,cap_unit);

    rwy.capacity_envelope = {rwy.cap_dep};

elseif findstr('MIXED_MODE',rwy.mode_ops)

    rwy=getArrCap(rwy,cap_unit);

    rwy=getDepCap(rwy,cap_unit);

    rwy=getArrDepArrCap(rwy,cap_unit);

    rwy=getMixPrioArrCap(rwy,cap_unit);

    rwy=getMixPrioDepCap(rwy,cap_unit);

% Collection of capacity results for the various points

cap_envelope = ...

    [0 rwy.cap_dep; ...

    rwy.cap_mix_prior_dep(1) rwy.cap_mix_prior_dep(2); ...

    rwy.cap_arr_dep(1) rwy.cap_arr_dep(2); ...

    rwy.cap_mix_prior_arr(1) rwy.cap_mix_prior_arr(2); ...

    rwy.cap_arr 0];

% Need to remove duplicated points

cap_envelope = unique(cap_envelope,'rows');

%NOTE : with unique, the resulting vector is sorted in ascending order,
but not in the order we would like for capacity envelope
```

```

    if ((cap_envelope(end-1,1)==cap_envelope(end,1)) && (cap_envelope(end-
1,2)<cap_envelope(end,2)))

        tmp = cap_envelope(end-1,2);

        cap_envelope(end-1,2) = cap_envelope(end,2);

        cap_envelope(end,2) = tmp;

    end

    rwy.capacity_envelope = {cap_envelope};

else

    display(['WARNING RunRWYCap: Mode of operations ' rwy.mode_ops '
unknown'])

end

%% Arrival Capacity Calculation (for arrivals only)

function rwy=getArrCap(rwy,cap_unit)

% calculation of probability of successive arrivals

rwy.inter_arr_prob=multiply_IJ(rwy.atm,rwy.atm);

% calculation of in-trail separation in time = max(arot,radar,wake vortex)
in sec

mias = max(rwy.mrs,rwy.miam); %get max between radar separation & wake
vortex in NM

rwy.airborne_inter_arr_sep_time=zeros(size(rwy.approach_speed,2));

for leading = 1:size(rwy.approach_speed,2)

    for trailing = 1:size(rwy.approach_speed,2)

        if rwy.approach_speed(leading)<=rwy.approach_speed(trailing) %
closing/overtaking case

```

```
rwya.airborne_inter_arr_sep_time(leading, trailing) = mias(leading, trailing) / rwy.  
y.approach_speed(trailing) * 3600;  
  
    else  
  
% opening case  
  
        if (rwy.egss == 0)  
  
% separation minima applied along the approach path when leading aircraft  
is at the entry gate  
  
            rwy.airborne_inter_arr_sep_time(leading, trailing) = (...  
  
                mias(leading, trailing) / rwy.approach_speed(trailing) ...  
  
                + rwy.approach_path *  
((1 / rwy.approach_speed(trailing)) - (1 / rwy.approach_speed(leading))) ...  
  
            ) * 3600;  
  
        else  
  
% separation minima applied along the approach path when trailing aircraft  
is at the entry gate  
  
            rwy.airborne_inter_arr_sep_time(leading, trailing) = (...  
  
                mias(leading, trailing) / rwy.approach_speed(leading) ...  
  
                + rwy.approach_path * ((1 / rwy.approach_speed(trailing)) -  
(1 / rwy.approach_speed(leading))) ...  
  
            ) * 3600;  
  
        end  
  
    end  
  
end  
  
end  
  
end  
  
end  
  
% max between AROT and minimum airborne separation
```

```
rwby.inter_arr_sep_time =
max(rwby.airborne_inter_arr_sep_time, repmat(rwby.arot(:), size(rwby.arot)));

%calculation of weighted average of in-trail separation in time (sec)

rwby.weigthed_avg_in_trail_sep_time=sum(sum(rwby.inter_arr_sep_time.*rwby.inter_arr_prob));

% Arrival capacity is ...

rwby.cap_arr=(cap_unit/rwby.weigthed_avg_in_trail_sep_time);

% additional calculation useful for reporting;

rwby.avg_approach_speed = rwby.approach_speed*(rwby.atm');

rwby.avg_airborne_inter_arr_sep_time=sum(sum(rwby.airborne_inter_arr_sep_time.*rwby.inter_arr_prob));

%% Departure capacity calculation (for departures only)

function rwby=getDepCap(rwby, cap_unit)

if (isfield(rwby, 'inter_dep_prob_precalculated'))

    % interdeparture time matrix inter_dep_prob_precalculated is (Trailing
A.B.C1.C2.D/Leading A.B.C1.C2.D vs different SIDS)

    % and needs to be transposed into (Leading A.B.C1.C2.D/Trailing
% A.B.C1.C2.D vs different SIDS)

    rwby.inter_dep_prob = rwby.inter_dep_prob_precalculated';

else

    %

end

if (isfield(rwby, 'inter_dep_airborne_sep_min_time_rsi'))
```

```
% interdeparture airborne separation minima matrix
inter_dep_airborne_sep_min_time_rsi is (Trailing A.B.C1.C2.D/Leading
A.B.C1.C2.D vs different SIDS)'

% and needs to be transposed into (Leading A.B.C1.C2.D/Trailing
% A.B.C1.C2.D vs different SIDS)

    rwy.inter_dep_airborne_sep_min_time =
rwy.inter_dep_airborne_sep_min_time_rsi';

else

    %

end

tmp_drot =
repmat(rwy.drot',size(rwy.inter_dep_airborne_sep_min_time,1)/size(rwy.drot,
2),size(rwy.inter_dep_airborne_sep_min_time,1));

rwy.inter_dep_sep_time = max(tmp_drot,rwy.inter_dep_airborne_sep_min_time);

rwy.weighted_avg_inter_dep_sep_time =
sum(sum(rwy.inter_dep_prob.*rwy.inter_dep_sep_time));

rwy.cap_dep=cap_unit/rwy.weighted_avg_inter_dep_sep_time;

%% Capacity Calculation when Alternating Arrivals and Departures, i.e.
pa=50

function rwy=getArrDepArrCap(rwy,cap_unit)

% The following calculation is based on averages weighted by fleet mix
only, i.e.

% the matrices are not provided.

if (isfield(rwy,'rwy_lock_dist'))

    if (~isfield(rwy,'weighted_avg_arot'))

        rwy.weighted_avg_arot = rwy.arot*rwy.atm';

    end

end
```

```
if (~isfield(rwy,'weighted_avg_drot'))
    rwy.weighted_avg_drot = rwy.drot*rwy.dtm';
end

rwy.weighted_avg_time_to_cover_rwy_lock_dist =
rwy.atm*((rwy.rwy_lock_dist ./ rwy.approach_speed)*3600)';

rwy.weighted_avg_inter_arrdeparr_time = (rwy.weighted_avg_arot +
max(rwy.weighted_avg_drot,rwy.weighted_avg_time_to_cover_rwy_lock_dist));

else

    if (isfield(rwy,'ads'))

        rwy.weighted_avg_inter_arrdeparr_time = rwy.atm*((rwy.ads ./
rwy.approach_speed)*3600)';

    else

        display('rwy.rwy_lock_dist or rwy.ads is missing');

    end

end

cap = cap_unit/rwy.weighted_avg_inter_arrdeparr_time;

rwy.cap_arr_dep=[cap;cap];

%% Capacity Calculation for Mixed mode of operations with pre-emptive
priority to Arrivals

function rwy=getMixPrioArrCap(rwy,cap_unit)

tmp = floor(...

    ((rwy.inter_arr_sep_time ...

    - repmat(rwy.arot',1,size(rwy.arot,2)) ...

    -

repmat(((rwy.rwy_lock_dist./rwy.approach_speed)*3600)',1,size(rwy.approach_
speed,2)))...


```



```
    ) / rwy.weighted_avg_inter_dep_sep_time) ...

+1);

rwy.squeezed_dep_btw_arrivals = max(tmp, zeros(size(tmp)));

rwy.weighted_avg_squeezed_dep_btw_arrivals = sum(sum(rwy.inter_arr_prob .*
rwy.squeezed_dep_btw_arrivals));

rwy.cap_mix_prior_arr = [rwy.cap_arr; rwy.cap_arr *
rwy.weighted_avg_squeezed_dep_btw_arrivals];

%% Capacity Calculation for Mixed mode of operations with pre-emptive
priority to Arrivals

function rwy=getMixPrioDepCap(rwy, cap_unit)

tmp = floor(...

    ((rwy.inter_dep_sep_time ...

-
repmat(rwy.drot', size(rwy.inter_dep_sep_time,1)/size(rwy.drot,2), size(rwy.i
nter_dep_sep_time,2)) ...

-
repmat(((rwy.rwy_lock_dist./rwy.approach_speed)*3600)', size(rwy.inter_dep_s
ep_time,1)/size(rwy.drot,2), size(rwy.inter_dep_sep_time,2))...

-
repmat(rwy.arot', size(rwy.inter_dep_sep_time,1)/size(rwy.drot,2), size(rwy.i
nter_dep_sep_time,2)) ...

    ) / rwy.weigthed_avg_in_trail_sep_time) ...

+1);

rwy.squeezed_arr_btw_departures = max(tmp, zeros(size(tmp)));

rwy.weighted_avg_squeezed_arr_btw_departures = sum(sum(rwy.inter_dep_prob
.* rwy.squeezed_arr_btw_departures));

rwy.cap_mix_prior_dep = [rwy.cap_dep *
rwy.weighted_avg_squeezed_arr_btw_departures; rwy.cap_dep];
```

```
function mult_ij=multiply_IJ(a,b)

a_tmp=(repmat(a(:),size(a)))';

b_tmp=repmat(b(:),size(b));

mult_ij=(a_tmp.*b_tmp)';

function displayRwySysCapEnvelope2D(cap_env,figTitle)

% Display Capacity Envelope

% the following should be a generic function within RunRunSysCap

figure('name','Theoretical Capacity Analysis');

set(gcf,'WindowStyle','docked'); % dock the figure in a figure container;
this creates a default value for the WindowStyle property on the root
level.

scatter(cap_env(:,1),cap_env(:,2),'r+');

hold('on');

plot(cap_env(:,1),cap_env(:,2),'r','LineWidth',2);

hold('on');

xlabel('Number of arrivals/hour');

ylabel('Number of departures/hour');

fig_title = sprintf('\fontsize{12}\bfBrussels National Airport - Runway
System Capacity Envelope');

title({'\fontsize{12}\bfCase Study - Brussels National
Airport'};{'\fontsize{12}\bfRunway System Capacity Analysis
2006'};{figTitle(1:end-2)}});

grid('on');
```

```
function displayRwySysCapEnvelope3D(cap_env,figTitle)

%meshc display of total capacity

figure('name','3-d representation of capacity envelope');

set(gcf,'WindowStyle','docked'); % dock the figure in a figure container;
this creates a default value for the WindowStyle property on the root
level.

x = [cap_env(:,1);0];

y = [cap_env(:,2);0];

z = x+y;

% can also use linspace function

xi = 0:max(x)/100:max(x);

yi = 0:max(y)/100:max(y);

% finer regular grid

[XI,YI] = meshgrid(xi,yi);

% default method

ZI = griddata(x,y,z,XI,YI, 'linear');

meshc(XI,YI,ZI);

hold('on');

colorbar;

plot3(x,y,z,'o','markerfacecolor','k');

xlabel('Number of arrivals/hour');

ylabel('Number of departures/hour');

zlabel('Total Capacity (movements/hour)');

title(['\fontsize{12}\bfCase Study - Brussels National
Airport'];'\fontsize{12}\bfRunway System Capacity Analysis
2006'];figTitle(1:end-2)]);
```

```
function displayTrafficMixProfile(pa_profile, figTitle)

figure('name', 'Traffic Mix Profile');

set(gcf, 'WindowStyle', 'docked'); % dock the figure in a figure container;
this creates a default value for the WindowStyle property on the root
level.

plot(pa_profile(:,4), pa_profile(:,3), 'b', 'LineWidth', 2);

hold('on');

xlabel('Arrival Percentage (%)');

ylabel('Total Capacity (movements/hr)');

title(['\fontsize{12}\bfCase Study - Brussels National
Airport']; '\fontsize{12}\bfRunway System Capacity Analysis
2006']; {figTitle(1:end-2)}]);

grid('on');
```

Appendix B – Acronyms

ACI	Airport Council International
AMAN	Arrival Management System
AMS	Airport Management System
ANSP	Air Navigation Service Provider
APATSI	Airport/Air Traffic System Interface
AROT	Arrival Runway Occupancy Time
A-SMGCS	Advance Surface Movement Guidance and Control System
ATC	Air Traffic Control
ATCSCC	ATC System Command Centre
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATRS	Air Transport Research Society
ATS	Air Traffic Service
BIAC	Brussels International Airport Company
BSC	Brussels Slot Coordination
CAA	Civil Aviation Authority
CAMACA	(EUROCONTROL) Commonly Agreed Methodology for Airport airside Capacity Analysis
CCC	(Belgocontrol) Capacity Coordination Cell
ccdf	complementary cumulative distribution function
cdf	cumulative distribution function
CDM	Collaborative Decision-Making
CFMU	EUROCONTROL Central Flow Management Unit
CIV	Chièvre (VOR in Brussels TMA)
CSSG	(Belgocontrol) Capacity Strategic Steering Group
DFS	Deutsche Flugsicherung
DGAC	Direction Générale de l'Aviation Civile (France)
DMAN	Departure Management System
DROT	Departure Runway Occupancy Time
EATM	European Air Traffic Management
EATMS	European Air Traffic Management System
ECAC	European Civil Aviation Conference

EPS	(FAA) Engineered Performance Standards
ESUG	European SIMMOD Users Group
EU	European Union
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	(US) Federal Aviation Authorities
FUA	Flexible Use of Airspace
GDP	Gross Domestic Product
HALS/DTOP	High Approach Landing System/Dual Threshold Operations Procedure
HUL	Huldenberg (VOR in Brussels TMA)
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
LP	Linear Programming
LU	Loughborough University
MACAD	MANTEA Airfield Capacity And Delay Model
MANTEA	Management of Surface Traffic in European Airports
MLS	Multi-lateration Landing System
MTOW	Maximum Take-Off Weight
NAS	(FAA) National Airspace System
NATO	North Atlantic Treaty Organisation
NLA	New Large Aircraft
OPAL	Optimisation Platform for Airports, Including Land-side
PANS-ATM	Procedures for Air Navigation Services : Air Traffic Management
PICAP	Programme of Investigation of Runway Capacity
PMI	Project Management Institute
ROT	Runway Occupancy Time
RWY	Runway
SARS	Severe Acute Respiratory Syndrome
SES	Single European Sky
SESAR	SES ATM Research programme
SID	Standard Instrument Departure
SIMMOD	Airport and Airspace Simulation Model

SPADE	Supporting Platform for Airport Decision-making and Efficiency Analysis
STAR	Standard Terminal Arrival Route
TAAM	Total Airspace Airport Model
TMA	Terminal Manoeuvring Area
TWY	Taxiway
UAV	Unmanned Aerial Vehicle
VFR	Visual Flight Rules
VLJ	Very Light Aircraft
VMC	Visual Meteorological Conditions
WWTUG	World-Wide TAAM Users Group

Appendix C – Descriptive Report of the Parties Involved

The Brussels Slot Coordination company (BSC) was created through a Belgian Royal Order on 26th June 2003, in order to implement EC Regulation 95/93 on slot scheduling. This order regulates slot allocation at Brussels Airport and sets up the status of Belgian slot coordinators, whilst ensuring their independency regarding the airport stakeholders. In practice, there is an implicit agreement between BIAC and Belgocontrol to provide airport planning expertise to BSC. Capacity analysis, used for the purpose of slot scheduling, is an issue that is predominantly addressed by Belgocontrol, because it is constrained by en-route and not only airport operations. In Belgocontrol, capacity is subject to specific working arrangements, as shown on Figure C-1, through the Capacity Strategic Steering Group (CSSG). The purpose of this group is twofold: first, to develop a company capacity strategy and, second, to give advice and consider specific operational/technical actions to enhance ATM capacity while maintaining and where possible improving safety, based on the company strategy. The CSSG work focuses on all relevant capacity programmes and projects taking into account environmental and punctuality issues. In addition, the CSSG is mandated to coordinate the Belgocontrol Capacity Strategy in national (including BSC) and international meetings. The CSSG therefore determines general guidelines, issues directives to the Brussels Airport Capacity Co-ordination Cell (CCC), and approves the transmission to the different ATC units of the developed plans.

The Brussels Airport Capacity Co-ordination Cell (CCC) is mandated by the CSSG to study all capacity improvement proposals and define capacity figures for all ATC units, ACC sectors and Belgian airports, including Brussels National Airport. In addition, it takes capacity enhancement measures where needed, whilst defining both the capacity contribution of new technologies and procedures and capacity reduction during contingency measures.

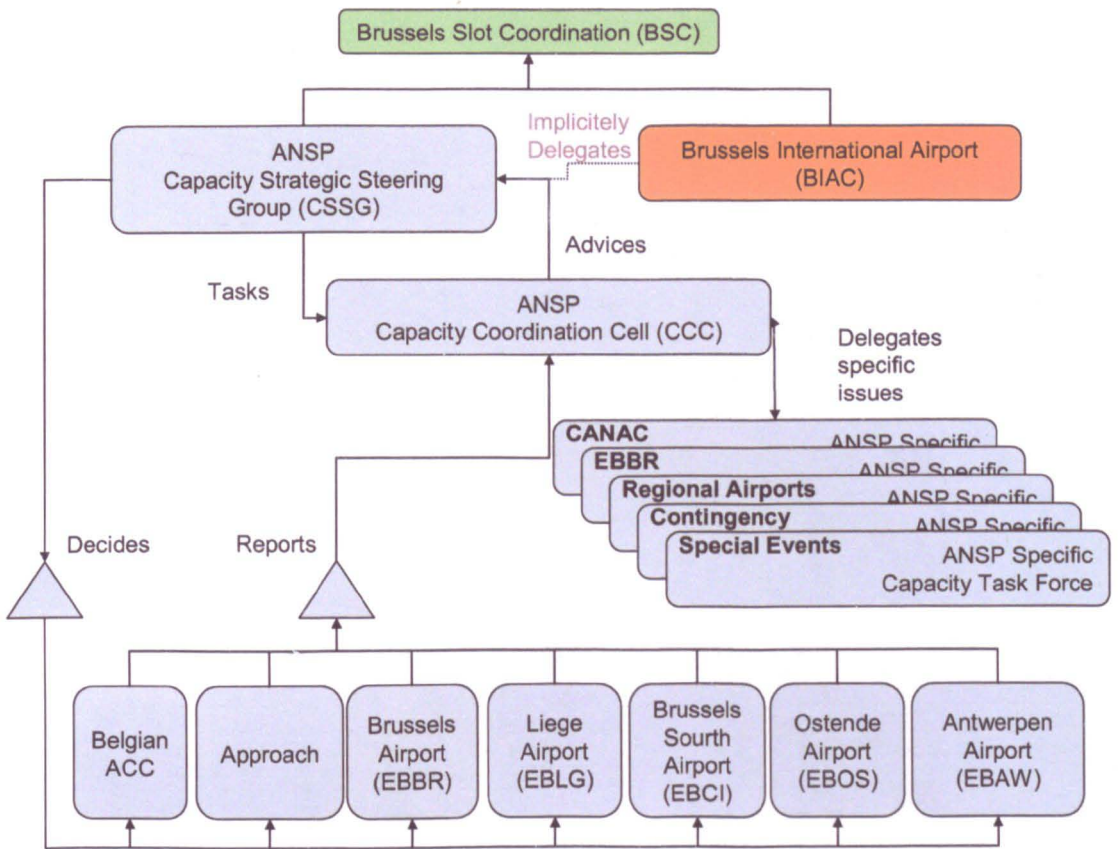


Figure C-0-1 – Strategic Capacity Working Arrangements