ABSTRACT

Successful air transport systems must satisfy the demand for flights while maintaining a high level of service and safety. For airports, which have limited capacities, policy-makers must compromise between maximizing the number of flights served and avoiding excessive delays. Differences between policies adopted in the US and in Europe result in distinct airport performances, the analysis of which reveals best practices.

The first point of comparison is over the capacities of a set of the busiest airports in the US and Europe. Under radar-based air traffic control procedures, Instrument Flight Rules (IFR), American airports achieve equal or higher capacities than European airports with similar runway layouts. These discrepancies cannot be explained by the differences in separation requirements alone. Besides, through their extensive use of Visual Flight Rules (VFR), weather permitting, American airports gain an important premium on their capacities. US air traffic control practices and policies clearly result in a more efficient use of airport infrastructure.

Second, arrival delays relative to schedule increase over the course of the day at the US airports, while they remain mostly constant in Europe. Similarly the distributions of these delays show that schedule reliability at airports is significantly better in Europe than in the US. These comparisons underscore the benefits of Europe’s policy of airport slot-controls, which cap the number of aircraft movements at a declared capacity. Moreover, arrival delays in the US are much higher under IFR (23 minutes average) than VFR (9 minutes). This shows that the high variability of the capacity of US airports depending on weather conditions, coupled with the tendency toward over-scheduling of flights, is damaging to the national airport system’s stability and reliability.

From these comparisons stem a few policy recommendations. Airline schedule reliability might benefit from additional controls or economic incentives to rationalize the scheduling of aircraft movements at some US airports. At the same time, some European airports could benefit from increasing their declared capacities. More generally, European aviation authorities should consider relaxing air traffic control separation procedures along the lines of US practices.

Thesis Supervisor: Amedeo R. Odoni

Title: Professor of Aeronautics and Astronautics and of Civil and Environmental Engineering
Acknowledgements

The two years I have spent at MIT and during which this thesis was written have been exceptionally interesting and instructive. I owe it to interactions with remarkable people. The time spent with these individuals was instrumental to the completion of this work thanks to both their academic insights as well their support and friendship.

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Many graduate students at MIT will tell you that an advisor can make your life on campus hell or heaven. I can vouch for that. Professor Amedeo Odoni, I am deeply grateful to you for hiring me as your Research Assistant, on the project that is the basis for this thesis. Thank you for making our research always pertinent and interesting and for sharing with me your invaluable experience of the industry. Thank you for guiding me attentively while giving me the flexibility of work pace and the freedom to pursue original research ideas; and for your unconditional support and motivating encouragements. Thank you for always going the extra mile in the laborious last minute paper editing, and for your help with the PhD application and the internship and job searches. I am truly perplexed as to how you maintained such high standards of guidance with the incredible amount of work you had in the year of 2009. Your leadership, your management style and your vision will always inspire me.

I also wish to address my most respectful gratitude to the Federal Aviation Administration for funding this project and especially to Mr. Dave Knorr for his trust and support. Thank you as well to the PRU and CODA team at EUROCONTROL for their generous collaboration.

Most of this work was done from my desk within the glamorous International Center for Air Transportation, at MIT’s department of Aeronautics and Astronautics. I was surrounded there with graduate students extraordinaire Claire, Ioannis, Olivier, Mehdi, Nikolas, Christopher, Varun, Gerasimos, Lishuai, Sarvée, Alexander, Diana, Nitish, Hanbong, Jonathan, Hongseok, Harshad, Emilio, Himanshu. Dear lab mates: you are smart, passionate and helpful. Most importantly, you are incredibly fun for work and play equally! You have helped me catch up with the knowledge of a research area that I knew little of. Many of the ideas I have had for this thesis can be traced back to interactions with you. Thank you for the many good times in and out of the lab, I wish you all the very best.

My thanks are also addressed to the professors associated with the ICAT laboratory, Prof R. John Hansman, Prof Hamsa Balakrishnan and Prof Peter Belobaba, as well as all the staff supporting ICAT, and Simon, one-time UROP helpful hand.
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1. Introduction

1.1 Background and motivation
Airports have airside capacities that are limited by (I) their infrastructure, especially the runway layouts, and (II) the utilization that is made of them, especially the air traffic control procedures for landings and take-offs. The constraint of airport capacity is known to often put a strain on air transport, and over-scheduling is one of the major causes of delays in commercial aviation. It was estimated that in 2008, delays cost $9.5bn to scheduled U.S. passenger airlines in direct costs, most of which can be traced back to extra fuel consumption and labor time. In addition, costs in terms of passengers’ time are estimated at $4bn (Air Transport Association of America, 2008).

Europe and the United States are two areas of the world where air transport has developed extensively over the past decades and has established itself as the dominant mode of long-distance transportation. A set of major commercial airports, connected by means of some of the most advanced air traffic management (ATM) systems in the world, provide the fundamental infrastructure for the respective air transport networks. Both the European and the US networks of airports are characterized by similar sizes and value; in both cases a majority of the flights (90%) are domestic to the system. As a result, the networks remain rather independent in their management. As a result, there exist some fundamental differences in the ways the networks are operated and in their performance.

In 2008, the Federal Aviation Administration (FAA) which operates the ATM system of the United States and EUROCONTROL, the organization responsible for coordinating ATM system planning, development, and operations in the great majority of European countries undertook a major study aimed at understanding the differences and similarities of the two ATM and airport systems and at identifying, when possible, best practices. A joint report has been issued (Enaud, Gulding, Hegendoerfer, Knorr, Rose, & Bonn, 2009) that presents the first findings of this study. The report deals with comparisons of many aspects of system performance, including flow management, en route, terminal area, and taxiway operations.

The work described in this thesis supplements the broader joint study. It is focused on major commercial airports and on the specific questions of how airside airport capacities, airport scheduling practices, and airport air traffic delays on the two sides compare. As will be seen, striking differences do exist in all these respects between airports in Europe and the US. At the root of these differences are the facts that (a) visual separation procedures are broadly utilized by the ATM system at US airports and (b) slot controls limit the number of operations that can be scheduled at the great majority of European airports, with the number of slots determined in most cases with reference to the capacity of these airports under instrument flight rules (IFR). The consequences of (a) and (b) are far-reaching; the resulting airport performance characteristics can also be seen as reflecting “cultural” differences regarding the principal operational objectives of the ATM and airport systems.
1.2 Research Outline

After presenting the stakeholders involved in the questions of airport capacities and delays (Section 2), the first part of this study is concerned with airport capacity. We define in Section 3 what is airport capacity and describe how it can be measured or estimated. Considering that airport capacity at major airports depends mostly on runway layouts, we then (Section 4) compare capacities of American and European airports that have comparable airfields. We next (Section 5) study the differences between air traffic control policies in the US and Europe and their impact on airport capacity. In the end we are able to assess which of the US or Europe has the most efficient air traffic control policies and practices, with respect to airside capacity.

The second half of the study is concerned with air traffic delays and the potential effects of over-scheduling. We present some theoretical background and explain how the study of delay performance can reflect the level of over-scheduling at an airport (Section 6). We compare not only average delays, but also the evolution of delays over the course of the day. In an attempt to gain perspective on the full cost of delays and to avoid the bias of airlines’ schedule padding, we also look at the distribution of delay around the averages, which is a reflection of the schedules’ reliability (Section 7).

By evaluating the two components of the trade-off between maximizing airport capacity and minimizing delays, we are finally able to conclude (Section 8) on the pros and the cons of both the European and the American systems. From these comparisons, best practices and policies are revealed and we suggest how the two systems can learn from each other in order to improve their management of air transportation.

Figure 1 – Aircraft queue at New York LaGuardia airport (The Port Authority of New York and New Jersey, 2008)
1.3 Literature review

The scientific study of airport capacity is almost as old as airports themselves; it has attracted a lot of academic interest in recent years as growing airport congestion put increasing pressure on the utilization of the airfield. Therefore, much of the theory of airport capacity was developed in recent decades; Gilbo’s breakthrough in airport capacity representation (on plane graphs, with one dimension for arrivals and the other one for departures) was published in 1993 (Gilbo, 1993), and one of the industry’s reference books on airport systems was published in 2003 (de Neufville & Odoni, 2003). The work of the MITRE Corporation for the FAA and major American airports is a good showcase of the possible methods for estimating airport capacity based on models and data observation (Federal Aviation Administration, 2004). On the European side, a very interesting recent study led by the Department of Airport and Air Transportation Research at RWTH Aachen University has created a framework for estimating airport capacity at the busiest European airports based on advanced analysis of exhaustive operational data.

Airport delays have been recorded, tracked, reported and studied for many years. The FAA publishes frequent and highly detailed reports on delay performance at American airports, while EUROCONTROL’s CODA and PRU units both produce interesting seasonal reports on the state of delays at European airports. The annual performance review reports provide yearly observations on the state of reliability of airport flight schedules in Europe (EUROCONTROL, Performance Review Unit, 2008). Although both the FAA and the European civil aviation authorities (see section 2.2.2) have been studying their systems independently for some time, the effort to establish points of comparison between each other is much more recent. The greater project (Enaud, Gulding, Hegendoerfer, Knorr, Rose, & Bonn, 2009) that this study is part of is one example of this effort.

There have been a few earlier efforts to compare US and European practices, some of them starting over 10 years ago. Donohue presents the results of a joint study (Donahue & Zellweger, 2001) by the FAA and EUROCONTROL Research & Development Steering Committee. The final report of this study (The R&D FAA/EUROCONTROL Committee, 2000) – which presented many interesting findings with respect to en-route air traffic control – however failed to compare the capacities of European and American airports in a way that could allow for performance assessments or policy recommendations. The observations of that study merely emphasized the fact that American airports have more runways and operate a greater number of aircraft movements.

In this light, there exists a real need in air transport research to establish valid capacity and delays comparisons. Such comparisons would permit to evaluate the true impact of the differences between US and European air transport policies and practices. This study intends to satisfy that need. It presents a more detailed and up-to-date comparison between the capacity performances of the US and European systems, and innovates by eliminating the biases of runway layouts. It also defines common measures of delay and applies them to both the US and Europe, to the extent permitted by the available data.

---

1 The study is part of a greater effort led by EUROCONTROL, the Air Traffic Management Airport Performance (ATMAP) project (EUROCONTROL, Performance Review Unit, 2009)
2. Stakeholders and framework of the study

2.1 Selected set of American and European airports

The study concentrated on the 34 commercial airports with the highest number of aircraft movements in 2007 in Europe\(^2\) and their counterpart set of 34 US airports. These airports are listed in Table 1 and Table 2, respectively, along with their traffic activity in 2007, which was the worst year in the history of aviation for airport delays (and the best year for the volume of air traffic). The US airports are also known as the “35 leading minus Honolulu” airports and are all in the continental United States.

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<th>Rank</th>
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Table 1 – 34 busiest European airports (aircraft movements, 2007) (Airports Council International, 2008)

The column “Declared capacity” in Table 1 indicates the number of slots available at each airport per hour. In the cases of several airports (for example LHR and FRA), the declared capacity varies slightly by

\(^2\) “European airports” in the above includes only airports in Member States of EUROCONTROL. Because Russia is not a member of EUROCONTROL (see Figure 2), Moscow’s Domodedovo Airport is not included in Table 1.
time-of-day to take into account the changing mix of arrivals and departures in the schedule. For these two airports, Table 1 indicates the greater number of available hourly slots per hour.

<table>
<thead>
<tr>
<th>Rank</th>
<th>City</th>
<th>IATA Code</th>
<th>Aircraft movements</th>
<th>Passengers</th>
<th>Optimal capacity</th>
<th>IFR capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Atlanta</td>
<td>ATL</td>
<td>980,386</td>
<td>85,907,423</td>
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<td>158-162</td>
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<td>927,834</td>
<td>76,159,324</td>
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<td>Dallas</td>
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<td>59,784,876</td>
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<td>186-193</td>
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<td>61,895,548</td>
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<td>117-124</td>
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<td>Denver</td>
<td>DEN</td>
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<td>49,863,389</td>
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<td>159-162</td>
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<td>LAS</td>
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<td>47,595,140</td>
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<td>42,978,617</td>
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<td>136-145</td>
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<td>35,160,505</td>
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<td>112-114</td>
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<td>110-113</td>
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<td>28,088,855</td>
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<td>57-60</td>
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<td>102-120</td>
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<td>19,378,546</td>
<td>64-65</td>
<td>61-64</td>
</tr>
<tr>
<td>27</td>
<td>Baltimore–Washington</td>
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<td>21,497,555</td>
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<td>Washington Reagan</td>
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<td>Tampa</td>
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<td>34</td>
<td>Pittsburgh</td>
<td>PIT</td>
<td>209,303</td>
<td>9,821,980</td>
<td>152-160</td>
<td>119-150</td>
</tr>
</tbody>
</table>

Table 2 – 34 busiest American airports (aircraft movements, 2007) (Airports Council International, 2008)

In Table 2, the two rightmost columns indicate the estimated capacity of each airport (number of runway movements per hour) under good weather conditions and in instrument meteorological conditions. The source of these estimates is the FAA Airport Capacity Benchmark Report (2004).
2.2 Aviation authorities
Countries manage the security, safety and efficiency of air transport within their territory and skies via some form of national aviation authority. These authorities are typically responsible for establishing and enforcing standards and certifications with respect to:
- Design of aircraft systems
- Design of airport systems
- Pilots and maintenance engineers
- Air traffic Controllers and their operations

Most of the time, air traffic control is an activity that is fully assumed by the aviation authority (meaning that the air traffic controllers and the relevant infrastructure are part of the aviation authority).

2.2.1 United States: the Federal Aviation Administration
For the United States, this agency is the Federal Aviation Administration, created in 1958 by act of Congress, and currently headquartered in Washington, D.C. with a budget for 2009 of over $16.7bn and over 35,000 employees (Federal Aviation Administration, 2009); the Administrator of the FAA is a presidential appointee. The FAA is fully in charge of air traffic control and often even manages airfield infrastructure improvements (in collaboration with airport authorities). In spite of its full control over all aircraft movement in the U.S., the authority of the FAA over scheduled aviation demand management – for example, the right to limit the number of scheduled arrivals and departures at an airport – has always been legally challenged and was never successfully established (more information in Section 8.4.1). The air transport philosophy in the United States is that airport capacity is a public good, and therefore all parties should be allowed access to it. Thus the FAA has been challenged whenever it has tried to place a cap on scheduled commercial movements; not to forget, on addition, that it is often under the obligation to accommodate non-scheduled general aviation (such as private airplanes, corporate jets, etc.). The system relies on the assumption that the air transport market will regulate itself and keep schedules at a manageable level.

2.2.2 Europe: EUROCONTROL, EASA and national agencies
Europe presents a unique case of cooperation between national Aviation Authorities. 38 countries of the European continent are members of the European Organization for the Safety of Air Navigation, or EUROCONTROL, an international organization with mission to “harmonize and integrate air navigation services in Europe, aiming at the creation of a uniform air traffic management (ATM) system” (EUROCONTROL, 2009). EUROCONTROL is independent from the European Union – some of its members are not EU countries and two EU countries are not members (Estonia and Latvia). EUROCONTROL was created in 1963 with 6 founding members and is today headquartered in Brussels (Belgium); its 2008 budget was close to €500 million and has about 2,200 employees (EUROCONTROL, 2009). Unlike the FAA, EUROCONTROL is not directly in charge of air traffic control in Europe, but rather coordinates air traffic efforts at a supra-national level; this explains the gap in budget and workforce between EUROCONTROL and the FAA. The two organizations are similar however in their research efforts to improve air transport practices. The Center Flow Management Unit, for example, aims at “enhancing

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3 The greater part of the FAA budget is spent in air traffic control staffing and infrastructure (e.g. towers)
safety through coordinated management of the air traffic in Europe and ensuring congestion in the air does not occur and that capacity is used effectively”. With a global perspective on the European network, the CFMU is able to prevent congestion by delaying some operations, in cooperation with local air traffic controllers. The decision-making role of EUROCONTROL attracted much media and public attention recently, during the 2010 volcanic ash cloud crisis in Europe.

Figure 2 – Map of EUROCONTROL Member States (EUROCONTROL, 2007)

The national Aviation Authorities of EUROCONTROL’s member countries remain in charge of the air traffic control in their skies, and still assume the core functions of traditional Aviation Authorities (operating air transport traffic, establishing and enforcing standards), although EUROCONTROL works to harmonize the different standards. The biggest national administrations in Europe are: the CAA (Civil Aviation Authority) for the United Kingdom, the DGAC (Direction Générale de l’Aviation Civile) for France, the LBA (Luftfahrt-Bundesamt, standards) and the DFS (Deutsche Flugsicherung, air traffic control) for Germany. Finally, the European Union is instigating the merging of its members’ aviation authorities into a single-sky, single-agency mode of operation. Some of the national authorities’ competences have already started to transition to the competent body: the EASA, the European Aviation Safety Agency (which took over many functions of the JAA, Joint Aviation Authority). The
increasing responsibilities already include: implantation of safety rules and type-certification of aircraft and components. More responsibilities are to come in 2013, including the certification of Functional Airspace Blocks, which are airspace blocks transcending state boundaries. Unlike EUROCONTROL, EASA remains a European Union agency, and non EU-member countries can choose to apply its recommendations but not be members.

### 2.3 Other stakeholders

There exist a few international organizations that are major stakeholders for the air transport industry. The ICAO, the International Civil Aviation Organization regroups 190 contracting states vowing to achieve the safe, secure and sustainable development of civil aviation. Headquartered in Montreal, it establishes air transport safety standards that individual Aviation Authorities can decide to implement, or modify into their own standards. The reference document for safety standards is the ICAO document 4444 (International Civil Aviation Organization, 2005). Many European National Aviation Authorities follow the recommendations of document 4444, at least for separation requirements (see Section 5.1). The United States follows its own FAA regulation.

The International Air Transport Association (IATA) regroups 230 airlines comprising 93% of all scheduled international traffic. Also headquartered in Montreal, IATA defends the interests of airlines against other stakeholders of the air transport industry, and is especially concerned with issues of demand management and slot control; for example the IATA has been extremely vocal in opposing the many attempts (from the FAA) at imposing slot control at American airports, especially the New York ones (International Air Transport Association, 2007). IATA has also organized annual slot auction conferences which process the slot exchanges of some the world’s busiest airports (that are slot-controlled), and devised rules to ensure the proper organization of slot auctions – they are followed by most today.

The ACI, the Airports Council International, regroups 597 members operating over 1679 airports in the world, which handle over 96% of the world’s air transport traffic. Headquartered in Geneva, Switzerland, ACI defends the interests of the airports on issues involving other stakeholders of the air transport industry. It is a primary source of data for air transport traffic, and publishes monthly and annually world traffic reports. The figures for number of passengers, aircraft movements and tons of freight in Table 1 and Table 2 are coming from such reports (Airports Council International, 2008).

### 2.4 Data

While numerous data sources have been used in this study, the most important ones for capacities were the airports’ individual declared capacities for Europe (as gathered by EUROCONTROL) and for the US, an FAA benchmark capacity report (Federal Aviation Administration, 2004) and movement rate estimates from the Aviation System Performance Metric (Federal Aviation Administration, 2007). For delays analysis, the study was based on the ASPM database (Federal Aviation Administration, 2007) and the CODA database of EUROCONTROL (EUROCONTROL, 2010).

#### 2.4.1 American airports capacities: FAA reports and ASPM

The FAA benchmark capacity report was prepared by the MITRE Corporation in 2004 in an effort to evaluate the progress made at America’s 35 busiest airports to increase capacity, by air traffic policies
and technologies improvements. The capacities are estimated based on experimental data observation and theoretical methodologies; they are declined for three kinds of weather conditions: Optimum, which represents Visual Meteorological Conditions, Marginal, which describes weather not good enough for visual approaches, but still better than instrument conditions, and IFR, for Instrument Flight Rules. These are the capacities that are provided, within ranges, in Table 1.

ASPM has capacity rates estimates for each airport that are dependent on runway configuration and weather condition (visibility, ceiling, wind). These are a second source of data for American airports’ capacities; they present the advantage of defining capacities under different runway configurations and different weather conditions, which can be interesting in order to make valid comparisons with the European airports. They are used in Section 4.

2.4.2 European airports capacities: individual airports’ declared capacities
Airports in Europe declare their own capacities (in collaboration with the Aviation Authorities). These capacities have a greater application than the FAA’s benchmarks or guidelines: they establish strict movement caps that scheduled aviation cannot exceed. These declared capacities are the ones that define the number of slots that are sold at auctions and traded among airlines. EUROCONTROL gathered declared capacities from a great number of European airports, directly from them, for 2008. These are the capacities given in Table 2.

2.4.3 American Airports delays: ASPM
The Aviation System Performance Metric (ASPM) database is very comprehensive, as it combines and compiles data from a variety of sources. For example, for each scheduled flight at every airport with commercial service, ASPM provides a record of scheduled and actual times of arrival at the gate, departure from the gate, take-off times, along with information about weather conditions at the time, runway configuration in use, etc. Both passenger and cargo flights are included. Other reports include counts of non-scheduled aviation (general aviation). Coverage is nearly complete, with only a small percentage of all flights are missing. Access to ASPM can be authorized upon request from the FAA and its use is subject to certain mild restrictions.

2.4.4 European airports delays: CODA
The CODA delay database (EUROCONTROL, 2008) is less complete, but very useful nonetheless. CODA relies on the airlines to report delay data on a voluntary basis, subject to strict confidentiality clauses. A majority, but not all, of the major European carriers are participating in the program. Low cost carriers, including Ryanair and EasyJet, do not. For the 34 European airports in our sample, 69% of all commercial flights are covered, with a range from 21% at Dublin to a maximum of 89% at Oslo/Gardermoen. There are also a few notable gaps in the data. For example, no or little information exists for many of the airports for movements taking place in the late evening and night hours, especially after 9 pm. Data coverage is generally better during daytime.

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4 It should be noted however that Ryanair, for one, usually has excellent on-time performance records
5 This is because when too few flights are on the record, the confidentiality agreement between the airlines and CODA does not allow for the sharing of data, so that airlines’ identities can be protected.
3. Definition of Airport Capacity

3.1 Definition of airport capacities, emphasis on runway capacity

Airports have 2 main users: passengers and aircraft. The handling of passengers occurs in the terminal buildings which oversee the core functions of airport access, check-in, security, immigration, customs, luggage handling, boarding; and support functions of parking, retail, customer services, airline operations. The space and infrastructure available for the core functions define a maximum passenger throughput capacity, which is the greatest number of passenger the facilities can process in a given period of time (ex: 1000 passengers per hour) and for a given minimum level of service (e.g. waiting time is less than 15 minutes, surface space per passenger is at least 1m²) (de Neufville & Odoni, 2003).

The handling of aircraft occurs on the airfield which oversees the core functions of landings, takeoffs, taxi in and out and gates. Aircraft movements on the runways (departures or arrivals) require separations to avoid accidents: aircraft create wake vortex which can render aircraft behind them unstable, as shown on Figure 3 in the example of landings on two closely-spaced parallel runways (i.e. separated by less than 2,500 ft). Runway infrastructures therefore define a capacity, just as the number of gates does. Similarly, taxiways have safety restrictions in order to avoid collisions, and define a taxiway capacity. Of all these capacities, the airport capacity is the capacity of the bottleneck infrastructure of airport: passenger buildings, gates, runways, capacities. The airports of our study are the busiest airports of the United States and Europe; and building runways require more space and effort than building passenger facilities. Therefore we assume for the 68 airports of our study that whenever one of them is capacity-constrained, it is because of its runway layout. This is the reason why we only consider the capacity of the runways, which is expressed in movements per unit of time. These movements can be either arrivals or departures. However, for practical reasons an airport needs to have the same number of aircraft taking off as the number of aircraft landing over a long period of time. Thus, finally we define for the particular purpose of this study:

**Definition**

The *Airport Capacity* is the number of aircraft movements (half of which are arrivals and the other half departures) that can be operated in one hour.
3.2 Capacity Pareto envelopes

In some cases, we may want to look at capacity in a broader sense than in this definition. Instead of only looking at the capacity where the ratio of arrivals to departures is 1, we can look at the capacity for any ratios of arrivals to departures, for example: all departures and no arrivals, all arrivals and no departures, 2/3 departures and 1/3 arrivals, etc. On a plane graph with the number of arrivals per unit of time on the x axis, and the number of departures per unit of time on the y axis, we can plot all the points that the airport can achieve in theory (coordinates: number of arrivals per unit of time, number of departures per unit of time), and draw the outer envelope of these points. That is the Gilbo curve (Gilbo, 1993). Here is an example of such hypothetical envelope, that we computed using the MACAD (Stamatopoulos, Zografos, & Odoni, 2004) model (see Section 5.1), applied to the runway layout of Munich airport (2 independent parallel runways, independent operations assumed):

![Diagram of achievable throughput points and airport capacity envelope]

Figure 4 – Theoretical airport capacities for Munich airport

**Definitions**

The area formed by all achievable throughput points (X arrivals per hour, Y departures per hour), in light blue in Figure 4, has for outer boundary the *Airport Pareto Envelope*. The intersection of this Pareto envelope with the bisector of the plan (X arrivals per hour, X departures per hour), which is the red dot in Figure 4, is the airport capacity, as defined in 3.1. In our example for Munich airport, that capacity is about 106 movements per hour (53 arrivals and 53 departures).
The Airport Pareto Envelope defines a convex area. The bisector of the axes of the graph (which is also the line made of all the points with equal ratios of arrivals and departures) intersects the capacity envelope at the point of capacity defined in 3.1. The convexity property is an important one: it is the theoretical argument that justifies drawing the capacity envelope based on experimental data, which do not represent all the possible throughputs (see Section 3.3).

**Property**
The points of achievable capacity (or “feasible throughput points”) form a convex area.

**Proof:**
To show this property, we must demonstrate that, for any given pair of points in the area, the points of the line segment joining the pair of points is also comprised within the area.

Let \(A(X_a,Y_a)\) and \(B(X_b,Y_b)\) be two points in the area. Let \(M(X_m,Y_m)\) be a point on the line segment \([AB]\). Therefore there exists a \(\lambda\) such as: \(0 \leq \lambda \leq 1\) and \(X_m = \lambda X_a + (1-\lambda)X_b\) and \(Y_m = \lambda Y_a + (1-\lambda)Y_b\).

For a large enough period of time \(T\), let now the airport operate for a time \(\lambda T\) with throughputs \(\lambda X_a\) arrivals/hour and \(\lambda Y_a\) departures/hour, and then operate for a time \((1-\lambda)T\) with throughputs \((1-\lambda)X_b\) arrivals/hour and \((1-\lambda)Y_b\) departures/hour. All are possible since points \(A\) and \(B\) are in the feasible throughput area.

Therefore, in a period of time \(T\), \(\lambda X_aT + (1-\lambda)X_bT\) arrivals and \(\lambda Y_aT + (1-\lambda)Y_bT\) departures were operated, which means that point \(M\) \((X_m = \lambda X_a + (1-\lambda)X_b, Y_m = \lambda Y_a + (1-\lambda)Y_b)\) is an achievable throughput.

### 3.3 Methods to estimate airport capacity

Estimating airport capacity accurately is important to airport planning and management. Overestimating capacity can lead to over-scheduling, where the demand for aircraft movements cannot be handled by the infrastructure, creating queues, delays and eventually a low level of service quality or a rupture of the system. Underestimating capacity can mean refusing access to scheduled flights that could have taken place, or barring entry to new competitors, which can be a cause for lower levels of competitiveness and, in the end, comes at a cost for the air transport consumer (see Section 8.1)

Airport Capacities can be assessed by methodologies of 2 sorts: either experimental (based on operational data) or theoretical (based on air traffic control rules and modeling of operations). For the experimental methodologies the maximum throughput of handled movements, over a long enough period of observation, can be an accurate estimation of the airport capacity provided a few assumptions:

- the demand for aircraft movements at the airport regularly exceeds capacity, so that the airport is capacity-constrained

- the airport is performing optimal operations
Drawing the Airport Pareto Envelope from there consists in finding the convex frontier of the plotted points. Some statistical precautions should be taken in order to eliminate outliers in the data set. For example, we have plotted the achievable throughput points for Newark, by plotting for each hour of 2007 the number of arrivals and the number of departures that were operated. We then selected only the points that occurred at a frequency equal or greater than 10 (which means 10 different hours out of an entire year of data, which is a frequency threshold of about 0.1%). According to this method, EWR has a capacity of 82 movements per hour (which is in line with FAA’s recommended cap of 81 movements). Some more elaborate, non-frequency based statistical tools exist to estimate capacity envelopes from experimental data, for example quantile regression (Ramanujam & Balakrishnan, 2009).

Capacities can also be assessed theoretically, based on a model of Air traffic control operations. For a given runway configuration, a model would typically take as an input the aircraft mix, the separation requirements, etc. and calculate the maximum throughput on the runways. As mentioned in 3.1, we are using the MACAD model to run the computations (which consist in calculating the probability of a succession of movements and then the average service time for a given movement). MACAD calculates certain key points of the capacity envelope and then, using the convexity property, draws the capacity envelope (an example is given in Figure 4, more computations in Section 5).
4. Capacity comparisons

4.1 VFR procedures in the US

Although the ATM system, facilities, and equipment at most of the European airports in Table 1 is as advanced as at airports in the United States – and in some cases, more advanced – there is a major difference in the way air traffic management is conducted. The United States operates, weather permitting, visual flight rules (VFR), under which pilots of landing aircraft are instructed by air traffic control to maintain visually a safe separation from the aircraft landing ahead of their own aircraft on the same runway. In bad weather, the US operates instrument flight rules (IFR) procedures, under which air traffic controllers are responsible for maintaining separations between aircraft on their radars. In contrast, IFR apply all the time at European airports, independent of weather conditions. VFR typically results in distances between successive landing aircraft which are, on average, smaller than the prescribed separation standards that are imposed in IFR; this affects greatly the arrival capacity of an airport. The net result is that the capacities of US airports under VFR are always higher than the capacities under IFR.

![Figure 6](image_url) – Parallel landings at SFO, with a third departing aircraft waiting (Gunawan, 2006)

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6 It is generally understood, however, that these requirements are relaxed, in practice, at a few of the busiest airports in Europe and air traffic control occasionally authorizes “experienced pilots” of some airlines that use the airport heavily to maintain visual separations on final approach in good weather.
VFR in the US are in theory applied in “visual meteorological conditions” (VMC), which are a number of weather requirements such as ceiling and visibility. The IFR equivalents are the “instrumental meteorological conditions” (IMC). For a number of practical reasons, however, IMC do not necessarily imply IFR and vice-versa – however it is impossible for us to know so since the data only records Meteorological Conditions and not Flight Rules. For the greater part of this study we therefore assume that both concepts imply each other.

Equally important, the separation requirements between aircraft operating on different runways may be relaxed when an airport is operating under VFR. For example, in good weather, simultaneous approaches (two aircraft landing side-by-side) are routinely conducted at SFO on parallel runways whose centerlines are only 740 feet apart (see on Figure 6 such parallel landings, with on addition a third aircraft taxiing between the two runways). Parallel landings are advanced air traffic control practices: the approaches of the two aircraft must be perfectly coordinated so that neither is affected by the wake vortex created by the other. In IMC, only one of these runways can be used for landings at a time. As a result, the capacity of SFO for landings is 54 – 60 per hour in VMC and only 32 – 34 in IMC (almost one half, as we could expect from parallel landings to a single file of landings to parallel landings).

Inspection of the two rightmost columns of Table 2 suggests that the difference between the VFR (“Optimal”) capacity and IFR capacity of many US airports is large. Moreover, airport weather information retrieved from the ASPM database indicates that VFR procedures are used in the large majority of time at the 34 US airports of interest. These 34 airports experienced VFR weather conditions in 2007 for 83% of the hours of the year, on average. The airport with the lowest percent of VFR conditions was Seattle (64% in 2007), and Las Vegas the one with the highest (almost 100%). In general, airports on or near the East and West Coasts had a relatively lower incidence of VFR weather.

If one uses the mid-points of the capacity ranges given in the two rightmost columns of Table 2 as the proxy values for the Optimal and IFR capacities of the US airports (e.g., 184 for Optimal and 160 for IFR in the case of ATL), then, on average, the VFR (Optimal) capacities are 29% higher than the IFR capacities. This gain is the result of the combination of higher capacities under VFR for arrival runways and of the ability to use combinations of two or more runways more efficiently under VFR. Taking the weighted average (83% of the time VFR, 17% IFR) results in an average capacity gain which is 26% higher than the capacity that would be available at US airports had these airports been operating under IFR all the time. Thus, the use of VFR procedures, weather permitting results in very large capacity increases at US airports, with the precise amount varying from airport to airport, depending on the layout of the runway system and the local weather conditions. In general, gains are smaller at airports with one runway (e.g., SAN has an 18% gain) or with widely separated runways (e.g., CVG where runway separations permit the independent operation of individual runways even under IFR and the gain is only about 10%); and they are larger at airports with complex geometries and closely-spaced parallel runways.
4.2 Slot control in Europe

Flight scheduling at airports in Europe is “slot-controlled”. This means that the number of movements scheduled at an airport is limited by the so-called “declared capacity” of the airport which specifies the number of slots available per unit of time – typically per hour, although limits for other time units (10 minutes, 30 minutes, flights per day, and sometimes a combination of these different time units, see for example Table 3 for Brussels airport) are occasionally used at airports with more elaborate slot controls. Airlines must acquire a slot for the right to land and depart at an airport at some particular time.

The declared capacity is typically set by the responsible National Aviation Authority, often in consultation with other entities (airport operator, airlines, air traffic controller representatives, etc.) – for details see (de Neufville & Odoni, 2003) and (Czerny, Forsyth, David, & Niemeier, 2008). For the European airports considered here, the procedures used to determine the declared capacity range from technically advanced – including the use of simulations and extensive consultation, as in the cases of LHR and FRA – to essentially ad hoc approaches with limited documentation. Once again, although theoretically the limit on the number of available slots is the capacity of the most constraining element of the airport (which may be the terminal building or the number of aircraft stands in the case of some smaller airports), for major airports such as those considered here the capacity of the runway system is practically always the one that determines the declared capacity.

<table>
<thead>
<tr>
<th>times / period</th>
<th>05 min</th>
<th>10 min</th>
<th>30 min</th>
<th>60 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>from</td>
<td>until</td>
<td>arr</td>
<td>dep</td>
<td>total</td>
</tr>
<tr>
<td>00.00</td>
<td>05.55</td>
<td>5</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>06.00</td>
<td>06.55</td>
<td>5</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>07.00</td>
<td>22.55</td>
<td>6</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>23.00</td>
<td>23.55</td>
<td>5</td>
<td>5</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 3 – Declared capacity table for Brussels airport (Brussels Slot Coordination, 2009)

The re-attribution of the slots takes place at a conference organized by the IATA, which sets a number of recommendations to ensure that a sufficient number of slots are auctioned for the market to remain competitive and that the entry of new competitors is possible. Airports may or may not follow all these recommendations; London Heathrow is a famous case where slots are extremely difficult to obtain, traded at very high prices between airlines – reaching as high as $60 million for a single pair of slots sold by Alitalia at the end of 2007 (Mutzabaugh, 2007). Entry of a new airline without many resources in the case of Heathrow is practically impossible.

In the United States, the concept of “declared capacity” is not used, in contrast to practically everywhere else in the world. The scheduling of flights at airports is not constrained: an airline may schedule a landing or takeoff at any time it wishes, as long as it can obtain access to a terminal building and aircraft stand. The exception is four airports, ORD, JFK, LGA and DCA (and formerly a fifth, EWR), known as the High Density Rule (HDR) airports, where the FAA has historically had the right to control to a varying extent the movement schedules. This however is not strictly speaking slot-control in the same way it is applied at European airports, and the FAA’s involvement in schedule management has always been legally challenged. For example, a slot auction was proposed but never conducted at LaGuardia.
airport in 2000 at the instigation of the FAA (Federal Aviation Administration, 2000). Later an attempt at organizing slot auctions at JFK and Newark airports also failed in 2009 (Federal Aviation Administration, 2009). The High Density Rule has now expired in the legal sense since 2007, but controls are still maintained, in somewhat relaxed form and under ambiguous legislation, by the FAA to mitigate congestion, especially at the three New York area airports.

One possible effect of slot-control is that protective schedule management may not give enough incentives to improve air traffic control practices and policies, and that therefore the runway infrastructure is not used to its greatest efficiency. The European and American airports offer an interesting comparison to test this possible effect: if slot control is negatively affecting airports’ capacities, then European airports achieve lower capacities than American airports with similar runway layouts.

Finally, another form of demand management is congestion pricing. The price of airport access can be increased at peak times in order to reduce demand and avoid excess. For example, at Heathrow in 2001, it cost £465 to land a small aircraft at a peak hour, to be compared with £195 off-peak (Odoni, 2007). Airport charges are strictly regulated in the US, where the cost must be justified by actual expenses, making landing fees much cheaper. Similarly to slot control, congestion pricing is therefore practically impossible in the US and attempts to implement it (for example, at Boston Logan) were unsuccessful when challenged in court.
4.3 Conjectures about the comparisons of US and European airport capacities

Comparing the capacities of US and European airports should shed light on the impact of several policy and practice differences between the two networks of airports. As noted already, European airports operate with Instrument Flight Rules in all weather conditions – at least officially. This means that the declared capacities of European airports are generally in line with the IFR capacities of these airports. In the US, the use of VFR creates capacities that are higher than IFR capacities. We saw that such a difference existed for American airports individually (+29% on average) and that this difference was significant in practice since VFR are operated for the greater part of the time (more than 80 of the time). We now propose to compare the capacities of airports with similar runway layouts, or using similar runway configurations, in the US and Europe. If the use of VFR in the US is indeed effective, the VFR capacities of US airports should be significantly higher that the declared capacities (IFR capacities) of European airports. This constitutes our first conjecture.

Going one step further, the IFR capacities of US airports would be expected to be generally somewhat in line with those of European airports with similar runway layouts. We propose to verify that on the same capacity comparisons. We conjecture however, that here too, IFR capacities will be often greater in the US than in Europe. We would see there the fact that airport authorities are often conservative in declaring capacities, either by choice, or because the practice of slot control is not giving the system enough incentives to have the best practices and research maximum airport capacity. This constitutes our second conjecture.

**Conjecture 1:**
*Due to their use of VFR procedures for much of the time, the VFR capacities of American airports are expected to be higher than the declared capacities of European airports with similar runway layouts*

**Conjecture 2:**
*Due to the use of slot control and schedule management, the declared capacities of some European airports may be underestimated, and lower than the IFR capacities of American airports with similar runway layouts.*

Conjecture 2 stands with the caveat that the safety requirements applied in IFR defer between the US and Europe. FAA’s IFR separation requirements (Federal Aviation Administration, 2008) are similar to but, in some cases, smaller than the requirements of the International Civil Aviation Organization (International Civil Aviation Organization, 2005) which are widely used in Europe. The impact, if any, of these differences will be studied in greater details in section 5. Therefore, whatever is proven in this Section regarding Conjecture 2 may be confirmed, nuanced, or even infirmed by the studies of Section 5.
4.4 Test of the conjectures for 5 runway configurations

To test the above conjectures we have tried to identify airports in the US and in Europe with similar runway layouts. This has proven difficult. The reason is that runway layouts tend to be much more complex in the US than in Europe: for our 34 top airports on each side, it turns out that the average number of runways per airport in the US is 4.12, while in Europe it is only 2.47\(^7\).

Most of the 34 airports in Europe have relatively simple runway layouts with a single runway or with sets of two or more parallel runways with a single orientation. By contrast, the great majority of the 34 airports in the US have at least one crosswind runway, i.e., at least one runway pointing to a direction different from that of one or more other runways at the same airport. We have examined five distinct runway configurations and identified airports in Europe and the US that operate one of these runway configurations. A few of them are shown in Figure 7 through Figure 11.

The five selected runway configurations comparisons all consist of parallel runways; runway layouts with crossing runways are more difficult to compare because they can be operated in completely different manners. For example, Frankfurt and Newark airports have very similar runway layouts (2 closely-spaced parallel runways plus a third crossing runway), but the two airports run completely different operations: Newark mostly uses the crossing runway to absorb excess demand for landings and operates the two parallel runways for segregated operations, while Frankfurt uses the 3\(^{rd}\) runway exclusively for departures while running mixed operations on the parallel runways.

Although 16 European airports\(^8\) from Table 1 have all parallel runways, only 4 American airports\(^9\) from Table 2 are in the same situation. The reason for that is that American airports very commonly have cross-wind runways. These runways are however not always used, and there exist 6 American airports\(^10\) from Table 2 which very frequently operate in all parallel runway configurations, without their crosswind runways. In order to have capacity estimates for these airports under those runway configurations, we have used ASPM’s arrival rates estimates (Federal Aviation Administration, 2007), rather than the earlier benchmark report (Federal Aviation Administration, 2004), because the latter only provides an overall capacity that is not runway-configuration specific.

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\(^7\) It should be emphasized that not all runways at an airport are active all the time. Because of their complex layouts, many US airports, especially, utilize only subsets of their runways, depending on weather conditions.

\(^8\) CDG, LHR, MUC, MXP, LGW, DUS, OSL, MAN, DUB, STN, ATH, PMI, NCE, GVA, STR, TXL

\(^9\) ATL, LAX, SEA, SAN

\(^10\) LGA, EWR, FLL, PDX, CLT, TPA
4.4.1 Configuration A: single runway

For Configuration A, a single runway configuration, the runway obviously operates with mixed operations. Departures are often alternating with arrivals, with two consecutive arrivals being spaced out just so that a departure can be inserted. Let it be noted that VFR procedures should not make a big difference for runway configuration A, since VFR affect separations between arrivals, which are here spaced out to insert a departure. LaGuardia is a two-runway airport (crossing), but operated for over 600 hours in 2007 in the 31|31 runway configuration (only in good weather conditions, however).

<table>
<thead>
<tr>
<th>United States</th>
<th>Europe (IFR assumed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airport</td>
<td>VFR</td>
</tr>
<tr>
<td>San Diego</td>
<td>48</td>
</tr>
<tr>
<td>LaGuardia (31</td>
<td>31)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
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<td></td>
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</tbody>
</table>

Table 4 – Capacity comparisons for runway configuration A

Both San Diego and LaGuardia airports achieve higher capacities than all European airports except for Gatwick. Airports such as Geneva and Stuttgart, especially, seem to have underestimated declared capacities; this seems to confirm conjecture 2. It should be noted however, that the estimation of 60 movements per hour on a single runway at LaGuardia seems an over-estimation, and that it is doubtful such a high throughput shall be easily achieved, even in good weather conditions and relaxed separation requirements.
4.4.2 Configuration B: 2 closely-spaced parallel runways

On a 2-closely-spaced-parallel-runway configuration (see Figure 2), we assume that an airport operates segregated operations: one runway for departures and one runway for arrivals. Close parallel runways are defined as being separated by less than 2500 feet (Federal Aviation Administration, 1989). For these operations, VFR procedures make a big difference: by reducing inter-arrival separation they increase the capacity of the arrival runway and therefore the overall capacity. As mentioned in 4.1 and seen on Figure 6, good weather conditions may also allow for parallel landings; however, parallel landings at Newark and Seattle are infrequent and the capacities given in Table 6 for these airports are the ones given by ASPM for segregated operations on the runways (no parallel landings). Seattle now has a 3rd parallel runway but the capacity estimate dates from before it was operational.

<table>
<thead>
<tr>
<th>United States</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airport</td>
<td>VFR</td>
</tr>
<tr>
<td>Seattle</td>
<td>72</td>
</tr>
<tr>
<td>Newark (4R</td>
<td>4L)</td>
</tr>
<tr>
<td>Newark (22L</td>
<td>22R)</td>
</tr>
</tbody>
</table>

Table 5 – Capacity comparisons for runway configuration B

This comparison shows us major differences between the IFR capacities of the American airports and the European airports in runway configuration B: both Seattle and Newark can achieve above 70 movements per hour, while Manchester’s and Dusseldorf’s capacities to not exceed 60 movements per hour.11

11 It should be noted however that some environmental constraints limit operations at Dusseldorf (in an effort to reduce noise pollution) (Boeing, 2010).
4.4.3 Configuration C: 2 medium-spaced parallel runways

On a 2-medium-spaced-parallel-runway configuration, we assume that an airport operates mixed operations on the 2 runways. Medium-spaced parallel runways are defined as being separated by less than 5000 feet, but still more than 2500 feet (Federal Aviation Administration, 1989). The operations are not completely independent on the 2 runways however, and a minimal diagonal separation of 1.5 nautical miles (nmi) (Federal Aviation Administration, 1989) must be observed between two aircraft landing on the 2 runways. Similarly to mixed operations on a single runway, the capacity of an airport under runway configuration C should not be heavily affected by VFR procedures, unless VFR operations affect the distance required between 2 runways to conduct independent operations, which is possibly the case for Portland airport below in Table 6 (capacity is 80 movements per hour in IFR, and 120 movements per hour in VFR – the latter being a rather optimistic capacity estimation).

<table>
<thead>
<tr>
<th>United States</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Airport</strong></td>
<td><strong>VFR</strong></td>
</tr>
<tr>
<td>FLL (9L,R</td>
<td>9L,R)</td>
</tr>
<tr>
<td>PDX (10L,R</td>
<td>10L,R)</td>
</tr>
<tr>
<td>PDX (28L,R</td>
<td>28L,R)</td>
</tr>
</tbody>
</table>

Table 6 – Capacity comparisons for runway configuration C

Although both Fort Lauderdale and Portland airports have crosswind runways they frequently operate without them. The 2-runway configurations were used at FLL and PDX for over 7,000 hours in 2007. Even if Portland is operating independent operations in VFR, the IFR capacities of the two American airports are 80 movements per hour, which is again above the capacity of the European airport under similar runway configuration: Milan Malpensa. Both conjecture 1 and conjecture 2 are therefore confirmed in the case of runway configuration C.
4.4.4 Configuration D: 2 independent parallel runways

On a 2-independent-parallel-runway configuration, we assume that an airport operates mixed operations on the 2 runways. Independent parallel runways are defined as being separated at their centerlines by at least 5000 feet (Federal Aviation Administration, 1989). Operations are an exact duplicate of the operations of configuration A, with a single runway.

<table>
<thead>
<tr>
<th>United States</th>
<th></th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airport</td>
<td>VFR</td>
<td>IFR</td>
</tr>
<tr>
<td>CLT (36L,R</td>
<td>36L,R)</td>
<td>131</td>
</tr>
<tr>
<td>TPA (18L,R</td>
<td>18L,R)</td>
<td>90</td>
</tr>
<tr>
<td>TPA (36L,R</td>
<td>36L,R)</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 7 – Capacity comparisons for runway configuration D

It should be noted that officially London Heathrow airport is operating its independent runways with segregated operations (one runway is used for arrival and the other one for departures, as in configuration B); however, since LHR’s capacity is 89, this would mean that a single runway is capable of handling 44 arrivals per hour, a very high throughput. Besides that possible exception of London Heathrow however, the declared capacities of Munich and especially Mallorca (90 and 60 movements per hour) are below the estimated IFR capacities of Tampa and Charlotte under configuration D (110 and 90 movements per hour). However CLT’s VFR capacity seems over-estimated (implying that each runway is capable of handling 65 movements per hour). In 2007, TPA and CLT operated over 8000 and 2,700 hours respectively in their 2-runway configurations. Conjecture 2, and conjecture 1 to a lesser extent, are both confirmed in the case of runway configuration D.
On a 2-pair-of-close-parallel-runways configuration, we assume that an airport operates segregated operations on each runway pair. Operations are an exact duplicate of the operations on runway configuration B, with one pair of close runways. In theory however, the expected capacity of 2 pairs of close parallel runways is slightly higher than twice the one of one such pair of runways; the reason is that with 2 arrival runways, air traffic control is capable to select and dispatch the arrivals among the 2 runways based on aircraft mix, so as to minimize inter-arrival separations.

<table>
<thead>
<tr>
<th>United States</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airport</td>
<td>VFR</td>
</tr>
<tr>
<td>ATL (26R,27L</td>
<td>26L,27R)</td>
</tr>
<tr>
<td>ATL (8L,9R</td>
<td>8R,9L)</td>
</tr>
</tbody>
</table>

Both Atlanta (at the time of the capacity assessment) and Los Angeles only have 4 runways, in runway configuration E; Atlanta now has a 5th independent parallel runway. They are therefore running the entire year in that runway configuration. It should also be noted that the separation between the runway centerlines at LAX are very small: 700 and 800 feet, which probably impedes on capacity. For example, when landing an A380 on one of the runways, the other runway (usually used for departures) has to be shut down, and the neighboring taxiway system is rendered unavailable.

Runway configuration E shows some very strong differences between the American airports and the European airports. It seems that the declared capacity of Charles-de-Gaulle airport is under-estimated, and that there is still room for a capacity improvement; indeed, the declared capacity at CDG has been gradually increasing over the past years, from 101 movements per hour in 2002 up to 112 movements per hour today. Both conjectures 1 and 2 are confirmed here.
4.5 Conclusions

It appears from the comparison of the capacities of runway configurations A through E that (1) the IFR capacities of the US airports are equal or above the declared capacities of the European airports\textsuperscript{12}, and (2) the VFR capacities of the US airports are much higher than the declared capacities of their European counterparts.

In other words, our two conjectures are confirmed: due to their policy of visual separations, weather permitting, US airports are able to make a much more efficient use of their infrastructure. Furthermore, it is possible that, due to their policy of slot-control, some European airports have declared capacities that are appear to have been underestimated, when compared to American airports. The exactitude of the latter statements remains to be confirmed by the study of differences in separation requirement policies, in the next Section.

These findings have important implications for airport utilization and scheduling practices on the two sides. In the case of European airports, there is little ambiguity: by definition, the declared capacities impose an upper limit on the number of movements that airlines may schedule during peak traffic periods or during any specified time interval. This limit, as we saw, is generally dictated by the IFR capacity of each airport – with the possible exception of such airports as LHR, FRA, and LGW.

In the United States, on the other hand – and with the exception of the former High Density Rule airports – there is only a perceived limit on how many movements can be scheduled in peak hours. Due to the high percentage of time when VFR procedures are in use, this perceived limit tends to be associated with the VFR (Optimal) capacity of busy airports. Thus, at the busiest airports, airlines schedule movements with reference to this optimal capacity, while recognizing that when weather conditions are less than good, the airport’s capacity will fall below demand and long delays will result. In fact, the airlines are under no legal obligation to adhere to any limit and the number of scheduled movements often exceeds even the optimal capacity at the most popular airports, especially for short intervals of time, such as 15 or 30 minutes.\textsuperscript{13}

The use of Optimal capacity as the reference point for scheduling purposes is also suggested by practices at the five US airports (ORD, JFK, LGA, EWR, and DCA) where ad hoc scheduling limits still exist. The scheduling limits set at these airports by the FAA are much closer to the capacity that these airports can attain under VFR than to their IFR capacity. Thus, the Optimal capacity is treated even by the regulatory authority as the best guideline for how many movements should be scheduled. The net result of all this is that US airports are generally called upon to handle a much heavier volume of aircraft traffic\textsuperscript{14} and are more heavily utilized on airside than European airports. In a sense, it can be stated that available airport capacity is utilized more efficiently in the US than in Europe.

\textsuperscript{12} Note the sole exception of London Gatwick, whose declared capacity is greater than the IFR capacity of San Diego
\textsuperscript{13} Ongoing research we are conducting shows that schedule frequently exceeds 23 movements per 15 minute intervals at Newark airport (Optimal capacity is 84-92 per hour)
\textsuperscript{14} Note that more aircraft traffic does not necessarily translate into more passenger traffic, as the latter also depends on the size of the aircraft utilized.
5. Impact of different air traffic control policies on airport capacities

One of the objectives of this study is to assess the impact of slot control on the utilization of airport capacity. The main causes of bias in comparing the capacities of different airports, namely the layout and utilization of the runway system, were eliminated in the comparisons that were made in part 4. Another important bias is the airports’ air traffic control policies. We have seen in Sections 4.1 and 4.4 the significant increase in airport capacity that results from the use of VFR procedures in the United States, in comparison with IFR procedures.

Could the differences observed, as per conjecture 2, between the declared capacities (IFR) of European airports and the IFR capacities of American airports – even with the same runway layouts – be explained by differences in air traffic control policies (different separation requirements, etc.)? To answer this question we have researched the air traffic control policies that are in use at the airports of the study and we have studied their impact on airport capacity, with the assistance of a computer model, MACAD (Stamatopoulos, Zografos, & Odoni, 2004).

5.1 Different separation requirements

Aircraft movements generate wake vortices (see Figure 3), which, in turn, create a potential safety hazard for the aircraft behind them. For this reason, air traffic control policies impose a set of separation requirements between consecutive aircraft operations that must be respected at all times:

- **Inter-arrival** separations: this is a driving factor in determining the all-arrivals capacity of a runway. The capacities of airports which use one or several runways for arrivals only are greatly affected by this separation, notably airports operating runway configurations B, C or E. This effect will be studied in Section 5.1.2.

- **Inter-departure** separations: this is a driving factor in determining the all-departures capacity of a runway. The capacities of airports which use one or several runways for departures only are greatly affected by this separation; notably airports operating runway configurations B, C and E. This will be studied in Section 5.1.3.

- Separations after a departure and a before consecutive arrival and vice versa: this is a driving factor in determining the capacity of runways used for mixed operations (alternated departures and arrivals). The capacities of airports which use one or several runways in mixed operations are greatly affected by this separation; notably airports operating runway configurations A and D. This will be studied in Section 5.1.4.

- Finally, many of these separation requirements vary depending on the weight of the aircraft (which impacts on the importance of the wake vortex that the aircraft generates as well as the sensitivity of the aircraft to weight vortices). Aircraft are classified in a few families based on their maximum take-off weight (MTOW). The mix of aircraft families therefore can have a great impact on airport capacity. London Heathrow, for example, has a greater concentration of heavy aircraft than all other airports in our set of 68 airports. The aircraft family classification will be explained in Section 5.1.1, and the practical effects of differences in aircraft mix on capacity will be studied in Section 5.2.
Each national Civil Aviation Authority may establish different standards for these separation requirements. In the case of our set of airports:

- US airports follow the standards recommended by the FAA (Federal Aviation Administration, 2008)
- UK airports follow the standards recommended by the CAA (Civil Aviation Authority, 2009)\(^\text{15}\)
- Italian airports follow the standards recommended by the ENAV (Ente Nazionale Assistenza al Volo, 2007) – which are a slight variation of the recommendation of ICAO (see below)
- other major European airports follow the standards recommended by the ICAO 4444 document (International Civil Aviation Organization, 2005). (CERFACS, BAE Systems, Airbus, 2001)

5.1.1 Aircraft classes

The ICAO classifies aircraft into 3 families based on their MTOW: Light (L), Medium (M) and Heavy (H). The United Kingdom classifies aircraft into 5 families: Small (S), Light (L), Lower-Medium (LM), Upper-Medium (UM) and Heavy. The United States classifies aircraft into 4 families, and are the only regulation with a family that is not based on the MTOW: Small (S), Medium (M), Boeing 757 aircraft (independently of their MTOW), and Heavy (H). These families and their definition are presented in Table 9.

<table>
<thead>
<tr>
<th>MTOW</th>
<th>0 tons</th>
<th>50 tons</th>
<th>100 tons</th>
<th>150 tons</th>
<th>200 tons</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICAO</td>
<td>0</td>
<td>7</td>
<td>M</td>
<td>136</td>
<td>H</td>
<td>---</td>
</tr>
<tr>
<td>FAA</td>
<td>S</td>
<td>19</td>
<td>M</td>
<td>116</td>
<td>H</td>
<td>---</td>
</tr>
<tr>
<td>UK-5</td>
<td>S</td>
<td>14</td>
<td>LM</td>
<td>104</td>
<td>UM</td>
<td>162</td>
</tr>
</tbody>
</table>

Table 9 – Aircraft classes based on MTOW for the FAA, ICAO and CAA’s UK-5 rules

It should be noted that at most airports in the world, and certainly at those of our study, the majority of the aircraft mix is made of Boeing 737s and Airbus A320s. These airplanes are often preferred by the airlines on short and medium-haul flights, which constitute the dominant part of air traffic movements at most airports. Both of these aircraft types belong to the “M” category of the ICAO, FAA and CAA (“LM”) classification schemes.

\(^{15}\) The CAA actually has 2 different set of regulations: one with 5 families of aircraft that applies at the 4 busiest airports in the UK (Heathrow, Gatwick, Stansted and Manchester) and one with 4 families of aircraft for the other airports. Since we are only concerned with the four busiest airports in our study, we only consider the first set of regulation, with 5 families, and refer to it as “UK-5”. (CERFACS, BAE Systems, Airbus, 2001)
5.1.2 Inter-arrival separation requirements

The inter-arrival separation requirements specify the minimum distance that must separate two aircraft landing on the same runway (or on 2 closely-spaced runways). This separation must be respected for the entire time that the aircraft spend on the final approach (typically 5-6 nmi ahead of the runway, although it is quite commonly less). Inter-arrival separations affect capacity critically when a runway is used for arrivals only; in that case capacity is almost directly inversely proportionate to the minimum separation requirements. Inter-arrival separation requirements depend on the aircraft family of both the “leading” aircraft (the one landing first) and the “trailing” aircraft (the one following). Indeed, depending on the size of the leading aircraft, more or less wake turbulence will be created, but depending on the size of the trailing aircraft, the tolerance to that wake vortex will vary as well; therefore the greater separation will be required between a large leading aircraft and a small trailing aircraft, whereas the smaller separation will be required between a small leading aircraft and a large trailing aircraft.

The separation requirements recommended by the FAA, the ICAO and the CAA are differ among each other and are summarized up in Tables 10, 11 and 12.

<table>
<thead>
<tr>
<th>FAA – MINIMUM INTER-ARRIVAL SEPARATIONS (nmi)</th>
<th>Leading aircraft family</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td>Trailing aircraft family</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>757</td>
</tr>
<tr>
<td></td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Table 10 – Inter-arrival separation requirements of the FAA</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAA (UK-S) – MINIMUM INTER-ARRIVAL SEPARATIONS (nmi)</th>
<th>Leading aircraft family</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td>Trailing aircraft family</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>UM</td>
</tr>
<tr>
<td></td>
<td>LM</td>
</tr>
<tr>
<td></td>
<td>L</td>
</tr>
<tr>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Table 11 – Inter-arrival separation requirements of the CAA</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ICAO – MINIMUM INTER-ARRIVAL SEPARATIONS (nmi)</th>
<th>Leading aircraft family</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td>Trailing aircraft family</td>
<td>H</td>
</tr>
<tr>
<td></td>
<td>M</td>
</tr>
<tr>
<td></td>
<td>L</td>
</tr>
<tr>
<td>Table 12 – Inter-arrival separation requirements of the ICAO</td>
<td></td>
</tr>
</tbody>
</table>
We highlighted in Tables 10, 11 and 12 and the most frequent separation (thus the most impactful), the one of the M-M pair (or LM-LM for the CAA); as mentioned earlier these are the most common families of aircraft and, therefore, the most common aircraft pair, as well. For example, on a typical day of operations (in October 2007), we estimated from flight statistics (flightstats.com, 2007) that over 80% of the aircraft belonged to ICAO’s family M (or CAA’s family LM) at the studied European airports, with only the exception of London Heathrow (61%). On the same day, 85% of the aircraft at San Diego airport belonged to FAA’s family M.

Most importantly, it appears that for the aircraft of these mid-size families, the separations are very similar: 3 nmi for ICAO, 3 nmi for the UK-5 (with LM-LM) and 2.5 nmi (or sometimes 3 nmi) for the FAA. We ran some computations to obtain an estimate of the impact of the variation of inter-arrival separations on airport capacity. These separations only affect the all-arrival capacity of a runway. To eliminate bias, we chose an identical aircraft mix, corresponding to a typical mix at busy airports, and consisting of [10% H, 90% M, 0% L] for the ICAO, [10% H, 5% 757, 85% M, 0% S] for the FAA and [10% H, 5% UM, 83% LM, 2% L, 0% S] for the CAA. We then ran a computer capacity model, MACAD, and obtained the following capacities:

<table>
<thead>
<tr>
<th>Arrival capacity under same aircraft mix</th>
<th>FAA (US)</th>
<th>CAA (UK)</th>
<th>ICAO (EUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32arr /h</td>
<td>28.9arr /h</td>
<td>29.2arr /h</td>
<td></td>
</tr>
</tbody>
</table>

Table 13 – Theoretical arrival capacities computed by MACAD under different ATC policies

It can be seen that the FAA’s air traffic control policies allow for an increase of about 10% in the arrival capacity of a runway, when compared to the ICAO’s or the CAA’s. This is mainly due to the smaller inter-arrival separation between medium-size aircraft (2.5 nmi v. 3 nmi).

5.1.3 Inter-departure separation requirements

The inter-departure separation requirements are a minimal time that must separate two aircraft departing from the same runway (or 2 closely-spaced runways). This time is counted between the instant the leading aircraft begins its takeoff roll at the runway and the instant the trailing aircraft starts rolling. Inter-departure separations will affect the capacity primarily when a runway is used for departures only. Inter-departure separation requirements also depend on the aircraft family of both the leading aircraft and the trailing aircraft. Indeed, depending on the size of the leading aircraft, more or less wake turbulence will be generated, and depending on the size of the trailing aircraft, the tolerance to the wake vortex will vary as well; therefore the greater separation will be required between a large leading aircraft and a small trailing aircraft, whereas the smaller separation will be required between a small leading aircraft and a large trailing aircraft.

The separation requirements recommended by the FAA, the ICAO and the CAA are somewhat different and are summarized up in Table 14, Table 15 and Table 16.
### FAA – MINIMUM INTER-DEPARTURE SEPARATIONS (minutes)

<table>
<thead>
<tr>
<th>Leading aircraft family</th>
<th>H</th>
<th>757</th>
<th>M</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trailing aircraft family</td>
<td>H</td>
<td>1.5</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>757</td>
<td>2</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>2</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 14 – Inter-departure requirements for the FAA

### CAA (UK-5) – MINIMUM INTER-DEPARTURE SEPARATIONS (minutes)

<table>
<thead>
<tr>
<th>Leading aircraft</th>
<th>H</th>
<th>UM</th>
<th>LM</th>
<th>L</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trailing aircraft family</td>
<td>H</td>
<td>1.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>UM</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>LM</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 15 – Inter-departure requirements for the CAA (UK-5)

### ICAO – MINIMUM INTER-DEPARTURE SEPARATIONS (minutes)

<table>
<thead>
<tr>
<th>Leading aircraft</th>
<th>H</th>
<th>M</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trailing aircraft family</td>
<td>H</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 16 – Inter-departure requirements for the ICAO

We ran MACAD once again with these different separation requirements for an all-departure runway with the same standard aircraft mix as in Section 5.1.2, and obtained the following results:

<table>
<thead>
<tr>
<th>Departure capacity under same aircraft mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAA (US)</td>
</tr>
<tr>
<td>53.6dep /h</td>
</tr>
</tbody>
</table>

Table 17 – Theoretical departure capacities by MACAD under different ATC policies

In all cases, the departure capacity remains well above the arrival capacities observed in Section 5.1.2. So in the cases of runway configurations with an all-departure runway (B, C and E), the overall airport capacity (50% arrivals, 50% departures), which equals twice the minimum of the arrival capacity and the departure capacity, is unaffected by the variations of the departure capacity.

Thus, for these configurations (B, C, and E) although the different separation requirements yield different departure capacities of the departures runway, this does not affect the overall capacities of the airports.
5.1.4 Mixed operations separation requirements

When an arrival is followed by a departure on the same runway, the rule is that as soon as the arriving aircraft has exited the runway and is on the taxiway system, the departing aircraft can start rolling. This rule is valid for all the airports of our study.

When a departure is followed by an arrival on the same runway, a minimum separation is required:

- In the US, the arrival must be 2 nmi away from the runway threshold.
- In the UK and in Europe, the arrival must usually be 3 nmi away from the runway threshold and, depending on the country, possibly more.

Let it be noted that this separation also depends on the existence of a missed approach diversion track and the angle of the latter with the departure track(s).

We ran MACAD once again with these different separation requirements for a mixed mode runway with the same standard aircraft mix as in Section 5.1.2, and obtained the following results:

<table>
<thead>
<tr>
<th>Mixed operations capacity under same aircraft mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAA (US)</td>
</tr>
<tr>
<td>57 = 28.5\text{arr} + 28.5\text{dep} /h</td>
</tr>
</tbody>
</table>

Table 18 – Theoretical mixed operations capacities computed by MACAD under different ATC policies

The different separation requirements of the FAA versus those of the ICAO or CAA highly impact on the capacity of a runway in mixed operations mode. The FAA requirements increase the capacity by about 15% (and possibly more in some countries). This is due to the separation requirement after a departure followed by an arrival (2 nmi v. 3 nmi).

5.2 Aircraft mix

The aircraft mix can theoretically impact airport capacity greatly: airports with a great variety of aircraft types may suffer from the varying separation requirements between aircraft of heterogeneous sizes. We mentioned however in Section 5.1.2 that at London Heathrow, which probably has the largest concentration of heavy aircraft of all the airports in our study, the share of smaller, “lower-medium” aircraft was still high, at 65%. As a matter of fact, the three London airports of our study present examples from the entire scope of possible aircraft mixes: Heathrow is a case of many heavy aircraft, Gatwick has a very significant number of heavy aircraft, but much less than Heathrow, and Stansted has almost no heavy aircraft.
We therefore computed the capacity of a single runway at each of these airports for uses varying from all-arrivals to mixed-mode to all-departures (see Table 19). This simple test suggests that:

- The aircraft mix does not affect at all the capacity of a runway in a mixed-operations mode. Because of the size of the required spacing between departures, and the increased spacing between the arrivals to accommodate departures, the inter-arrival and inter-departure separations are not affected by the change in aircraft mix.

- The aircraft mix affects the departure capacity of a runway in an all-departures mode. However, as mentioned earlier, the departure capacities are still sufficiently high (above 45 departures per hour) that the overall capacity of airports with two or more runways may not be affected.

- The aircraft mix affects the arrival capacity of a runway in an all-arrivals mode. The effect is rather minor, however: a difference of only 1 arrival per hour between Gatwick and Heathrow and of another arrival per hour between Stansted and Gatwick.

Differences in aircraft mix at the airports of the study have no impacts on mixed-operation runways; however they may affect the arrival capacity of a runway with an increase of up to 7% arrivals per hour. The effect on the departure capacity of a runway has limited or no impact on the overall capacity of the airport as a whole.
5.3 Conclusions on the effect of different air traffic policies on airport capacities

For airports operating in runway configurations A and D, the differences in separation requirements between departures followed by arrivals between the US and Europe can explain up to a 15% difference in airport capacity (in favor of the US). For airports operating in runway configurations B, C and E, the different inter-arrival separation requirements between the US and Europe can explain up to a 10% difference in airport capacity (in favor of the US). Overall, therefore, the separation requirements in the US increase by maximum 15% the capacities that would be seen with European separation requirements.

Finally, for airports in runway configurations B, C and E the differences in the airports’ aircraft mixes can explain up to a 7% difference in the airport capacities (in favor of the airports with fewer heavy aircraft).

The differences between US and Europe (up to 15%) are not sufficient to explain the entire gap between the IFR capacities of US airports and the declared capacities of European airports (see Section 4.4), as pointed out by conjecture 2:

- for runway configuration A, the gap is as high as 33% (Geneva – San Diego)
- for runway configuration B, the gap is as high as 52% (Dusseldorf – Seattle)
- for runway configuration C, the gap is as high as 30% (Milan – Portland)
- for runway configuration D, the gap is as high as 50% (Mallorca – Tampa)
- for runway configuration E, the gap is as high as 48% (CDG – Atlanta)

This theoretical test on the impact of different separation requirements on airport capacities therefore confirms our conjecture 2: the declared capacities of some European airports are probably underestimated, when compared to the practices applied at American airports (or other European airports). The cause for these under-estimations could be inherent to the inherent nature of slot-control policies, which may not encourage the application of best air traffic control practices and the declaration of maximum capacities.
6. Air traffic delays at airports: background
Sections 4 and 5 suggest that the available airport infrastructure is, for the most part, utilized more efficiently in the United States than in Europe, in the sense that airports in the United States are generally able to serve more aircraft movements per unit of time than airports with similar runway layouts in Europe. The primary reason for this is the use of VFR procedures, weather permitting, at US airports, while a secondary explanation is the apparent occasional underestimation of declared capacities at some European airports.

6.1 Measures of level of service on airside
A central question, however, is whether the more efficient utilization of the infrastructure in the US also results in a significant deterioration in the level of service provided to the airports’ users. To address this question we look next at two critical measures of level of service (LOS): delay and schedule reliability. The analysis is for 2007.

We shall concentrate first on the delay metric which is of greatest interest to travelers, namely delay relative to the scheduled arrival time at the gate. This measures the difference between the time when a flight was expected to arrive at its gate at the destination airport and the time when it actually arrived. Arrival at the gate is also the final stage of a flight leg, and therefore reflects the accumulation of delays over all the previous stages: gate out, taxi out, en route, final approach, taxi in. Note also that, an aircraft can be late, relative to its scheduled arrival time, not only because of local congestion, but also because the aircraft in question was late on departure from its origin airport due to delays it had suffered on earlier flights.
In other words, a delay can be due to any combination of *local* delay (at the airport of destination) and of *propagated* delay from earlier flights\(^{16}\). In a network in which many of the airports are congested, it is therefore possible to observe large delays (relative to schedule) even at airports which are not congested, as a result of propagated delays. In this sense, our measure — delay relative to the scheduled arrival time — can be considered as much an indicator of system-wide performance, as of performance at the individual airport level.

Besides selecting a measure of delay for each flight, one must also define a more aggregate measure of delay that would summarize overall system performance. In the literature this measure is usually the average minutes of delays above a 15-minute threshold (Enaud, Gulding, Hegendoerfer, Knorr, Rose, & Bonn, 2009), or sometimes a 0-minute threshold. This choice is made on the grounds that only the minutes of delays beyond such a non-negative threshold are damaging to the industry and its stakeholders. However, due to the widespread use of block time padding by the airlines, we think it best to consider all delays relative to schedule. Therefore we calculate the average value of delay, including the flights with negative delays. Finally, in order to estimate the average flight delay at an airport during a given hour, we consider all flights that were scheduled to arrive within this particular hour, rather than the flights that actually arrived at that particular hour. This way the average hourly delays are high at the times when the aircraft queue is long and building up, rather than later, when the queue size is actually decreasing.

In addition to averages, we examine the distribution of the delays. *Schedule reliability* refers to measuring the extent to which passengers can rely on the advertised timetable of flights at an airport. To assess schedule reliability one must look not only at the average delay relative to schedule, but also at the distribution of delay around that average. The larger the variance (or standard deviation) of that distribution, the less predictable flight operations are, implying low schedule reliability. Sections 7.3 and 7.4 will consider this topic.

### 6.2 Queuing theory

Although modeling delays is not as important to managing an airport as modeling capacity, the quantitative study of the dynamics behind the creation of delay is central to understanding how variations in the schedule of flights may affect airport-related delays.

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\(^{16}\) In the United States, propagated delay is usually referred to as “upstream” delay and in Europe as “reactionary” delay.
Queuing theory – see, e.g., (Larson & Odoni, 1982) – provides the methodology for studying delays at airports. An airport is viewed as a queuing system, consisting of a demand stream, described by a demand rate and an associated probability distribution for demand inter-arrival times, and a service rate and service time distribution (Figure 13). The processing of arrivals and departures may be treated as separate queuing systems, when some runways are used solely for arrivals and others solely for departures, or analyzed through a single queuing system when runways are used in mixed mode.

It is often assumed, as an approximation, that the demands in such a queuing system constitute a Poisson process, with a demand rate equal to \( \lambda \) operations per unit of time (arrivals, departures, or mixed operations, as the case may be). This means that the probability that \( k \) demands will occur during an interval of time \([0,t]\) is given by:

\[
P_k(t) = \frac{(\lambda t)^k}{k!} e^{-\lambda t}
\]

Let now the service rate at the runway system be equal to \( \mu \) operations per unit of time and let \( \sigma^2(S) \) indicate the variance of the service time for each operation on the runway. Finally, let \( \rho = \frac{\lambda}{\mu} \) denote the “utilization ratio” of the runway system. (Intuitively, \( \rho \), the ratio of the demand rate divided by the service rate, is a measure of the intensity with which the runway system is being utilized.) Then, an important result of queuing theory – see, e.g., (Larson & Odoni, 1982) – states that the expected waiting time per operation in the queue at equilibrium (i.e. in a stable regime or “steady-state”) is given by:

\[
W_s = \frac{\rho^2 + \lambda^2 \sigma^2(S)}{2\lambda(1 - \rho)}
\]

The \( 1/(1-\rho) \) factor in this expression indicates that the expected waiting time (and the queue of operations) grows very quickly when demand is near capacity (i.e., \( \rho \) is near 1). Figure 14 below shows this schematically and underscores the highly nonlinear relationship between the expected waiting time and the utilization, \( \rho \), of a system of runways at an airport.

Figure 14 – theoretical delays as a function of demand (Larson & Odoni, 1982)
The important take-away here is that, for an airport where utilization ratio $\rho$ is very close to 1, a small variation in demand can have enormous impacts on capacity. This is a supporting factor in the European philosophy of slot control, by which great value can be gained in on-time performance with little costs in reduction of demand.

6.3 The Delays model, some runs for European and American airports

A model, called DELAYS (Kivestu, 1976), has been developed at MIT for estimating approximately the delays at an airport for a given demand profile and a given airport capacity profile. The model provides a simple, yet efficient engine for airport delays computations and can also be used as a component of more elaborate computational tools – see, for example (Pyrgiotis, Malone, & Odoni, 2010). In DELAYS, both the demand and capacity profiles can be time-varying and are typically described by providing the hourly demand and service rates at the airport over a 24-hour period. The model makes the following simplifications: arrivals and departures are merged into a single-demand stream, with a common service rate. The demands are assumed to constitute a non-homogeneous Poisson process, while the service times are modeled through a k-th order Erlang probability density function – for our computations an “order 9” Erlang was used. Thus, DELAYS is an $M(t)/E_k(t)/1$ queuing model in the standard notation of queuing theory (Larson & Odoni, 1982).

The DELAYS model can be used to obtain theoretical estimates of delays at an airport with realistic, dynamic demand and capacity profiles. An example is provided in Figure 15 where we have computed delay estimates at Newark airport for the last Wednesday of March 2007, 2008, and 2009. The figure presents the demand profile at Newark in terms of hourly movements (scale on left vertical axis) and the estimated average delay per movement (scale on right vertical axis) on the three days in question, under the assumption that the capacity throughout the day is equal to 81 movements per hour, which the FAA considers to be the nominal capacity of EWR (Federal Aviation Administration, 2008).

It is important to select individual days of operations for the demand input in the DELAYS model in order to obtain a realistic picture of the associated delays. Even though individual days are not representative of the entire year, running DELAYS with a demand profile which represents an average over the entire year would create low, unrealistic delays. Indeed, the variation of demand from one day to the other is the source of peaks in the demand profile, which create much higher delays than if this extra demand were averaged over 365 days. The theoretical explanation behind this is the non-linearity of delays with respect to demand (Figure 14).
Figure 15 – Theoretical delays at Newark airport for different days’ schedules
In Figure 15, the changes in the schedule at Newark airport between 2007 and 2009 produce some remarkable differences in the delay performances, as estimated by the DELAYS model. The total number of movements scheduled for these dates declined only slightly over the three years: 1248 movements in 2007, 1214 movements in 2008 and 1197 movements in 2009, for a total decrease of 4% between 2007 and 2009, probably related to the global economic downturn. This rather insignificant decrease, however, occurs at a level of demand scheduling that is very close to the capacity of the airport. As can be seen in Figure 15, the hourly demand rate at Newark, especially in 2007, was at or above the nominal capacity of the airport (81 movements per hour) for several hours in the day. As a result, the estimated delays are reduced by a much greater proportion than 4% between 2007 and 2009: the average hourly delay peaks at 30 minutes in 2007, at less than 20 minutes in 2008 and at less than 10 minutes in 2009! In other words, a 4% reduction of the demand is reflected in a 70% reduction in the peak average hourly delay of the day. This is a very striking illustration of the non-linearity of airport delays at demand levels close to capacity.

6.4 An argument in favor of slot control

The European practice of “declaring capacities” can be viewed as an effort to capitalize on this non-linear relationship between delays and airport demand: a small reduction in demand (as a result of setting an upper limit in the number of flights that can be scheduled at an airport) may mean the loss of a few flights, but also a large gain due to significantly fewer delays. If there really exists for each airport a strict maximum throughput threshold, beyond which demand cannot be handled any more, then declaring capacity near (in fact, slightly below) that level is the most sensible policy. Indeed, under these assumptions, there exists an equilibrium point where the losses in capacity and the gains in delays are equal to each other. This equilibrium point defines the level at which the declared capacity should be set. It is estimated that the declared capacities are typically set at 10% below maximum throughputs (de Neufville & Odoni, 2003), which means that the afore-mentioned equilibrium point may be situated at a utilization ratio of \( \rho = 0.9 \).

These assumptions and reasoning would lend support to the European philosophy of airport slot control, which is implemented by the airport slot coordinators and the national Civil Aviation Authorities. On the contrary, the American philosophy of airport scheduling, supported by the airlines, challenges the idea that the maximum throughput is an inflexible value. Supporters of the US approach also contend that, by declaring a capacity, airport operators and air traffic control authorities are under less pressure to adopt best practices and maximize capacity. Indeed, we have found in Section 4 that the FAA separation requirements allowed for a higher throughput than the ICAO ones, especially due to the use of VFR procedures. It could very well be that in a more conservative air traffic control environment such efficient practices would maybe not have been researched, conceived and implemented. There exist some historic and cultural reasons why different philosophies prevail between the US and Europe, and these will be explored further in Section 0.
7. Analysis of delay data

We described and explained in Section 6 the different measures of delays and their significances. With regards to our study, we want to study the impact of the differences in policies between the US and Europe on over-scheduling, which leads to low level of service. According to Queuing theory, the most direct consequences of over-scheduling at airports are the queues of aircraft that wait to be processed by the system\(^\text{17}\). It is difficult to estimate these queues based on the available US data, and impossible with the European one. This is the reason why we opt to study the less direct consequence of over-scheduling: scheduled flights delays. Furthermore delays are the most relatable measure of the level of service of air transport.

To that purpose, we have selected a particular measure of delay (the reasons for which are outlined in Section 6) that we will analyze in this section:

- for each flight arriving at one of the selected 34 airports in the US or in Europe during the year 2007, we calculate the difference between the actual time of arrival at the gate and the scheduled time at the gate;

- when calculating average hourly delays, we compute the average of these individual delays (including negative values) across all the flights that were scheduled to arrive at the gate within this particular hour. For example, the average hourly delay at 3pm is the average of the delays suffered by all the flights whose scheduled time of arrival was between 3:00:00 and 3:59:59.

7.1 VFR v. IFR in the US

Before comparing the US airports against the European airports, we try to study the impact of IFR and VFR in the US. To study the impact of using two different sets of air traffic control procedures, depending on weather conditions, we compared arrival delays (relative to schedule) at US airports for VFR weather vs. IFR weather. Specifically all flights at the 34 US airports were separated into two categories:

- “IFR flights”, defined as those flights whose scheduled arrival time fell during a period of Instrument Meteorological Conditions (IMC) at the destination airport\(^\text{18}\)

- “VFR flights”, all the other flights.

Figure 16 shows that average delays, computed for all flights in 2007, are strikingly higher for IFR flights than VFR flights. The average delay over the interval of time considered (7am – 10pm) is 9 minutes for VFR flights, versus 23 minutes for IFR flights, i.e., the impact of reduced capacity in IMC is an increase of

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\(^{17}\) These queues of course do not exist physically, the aircraft are actually waiting at different locations of the airspace, en-route or even on hold at the origin airport (See Ground Delay Programs in Section 8.1.3)

\(^{18}\) The Meteorological conditions (IMC or VMC) information is based on weather data at the airport. It detects conditions in which the air traffic control should operate visual or instrumental separations. In reality, the control tower may not follow strictly speaking what the weather data recommends, especially when the weather is very variable.
the average delay by 150% (while the average decrease in capacity is 29%, as estimated in Section 4.1). This is again a good example of the non-linear relationship between capacity and delay, when demand is close to capacity (cf. Section 6.2).

Figure 16 – Average arrival delay relative to schedule at 34 busiest US airports in 2007

Figure 16 is also the confirmation of the observation that, when airlines schedule flights at US airports, they use the VFR capacity of the airports as their notional point of reference. Thus, when weather conditions do not permit VFR procedures and capacity falls short of the notional expectations, delays become extremely large. Note that in IMC, the average delay relative to schedule over all 34 airports was above 30 minutes (!) from 3 pm to 9 pm local time in 2007 – a situation that many would consider unacceptable. We remind the reader that such conditions prevail for about 17% of the time (Section 4.1) or, roughly, 1 out of every 6 days. As well, such conditions do not occur at all airports at the same time and therefore on most days, at least a few major US airports will be in IMC. Thus, well-connected US airports may suffer on almost a daily basis from delays that occur due to bad weather at other airports.

Although weather conditions obviously vary at European airports19, as well, the use of IFR procedures at all times means that they experience far less capacity variability than US airports. One can therefore speculate that the performance of European airports with respect to air traffic delay is less dependent on weather than at US airports. Unfortunately, the absence of relevant information in the CODA database makes it difficult to classify European airport operations into “VFR” and “IFR” as was done for US airports in Figure 16 and thus to confirm or refute this conjecture20.

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19 For example, detailed data from Frankfurt Airport, shows that conditions corresponding to the definition of IFR weather in the US prevail at FRA for about 12% of the time, in line with what is typical of US airports.
20 We are in the process of testing the conjecture through the analysis of the detailed data from FRA.
7.2 Europe and US delay performance overview

We next compare average delays by time-of-day for all weather conditions at the airports of interest. We have selected for this purpose the principal time window for airport operations, i.e., the period between 7 am and 11 pm (local time for each airport). The results are shown in Figure 17. For example, flights at the 34 US airports which were scheduled to arrive at their destination airport between 4 and 5 pm local time were, on average, about 15 minutes late in 2007.

Unfortunately, as noted in Section 2.4.4, European data for the time from 10 pm onwards are sparse and possibly non-representative as they are unevenly distributed among airports and airlines. We shall therefore limit any comparisons to the time until 10 pm (which is until the 9pm hourly average). Figure 17 shows two different patterns for average delays in the US and in Europe. For the former, delays increase steadily through the course of the day, until they reach their maximum level at about 9 pm – declining subsequently during the late night and early morning hours. For Europe, by contrast, average delay relative to schedule remains remarkably constant during the greater part of the day and, after 3 pm, at about one-half the level of delay at US airports.

Since we are calculating delays for the time at which flights were scheduled to arrive, an increase in the hourly average delay means that the queue of arriving flights has built up over the past hour. In other words, this suggests that in the US, from the very beginning of the day until the late hours of the evening, the schedule is consistently too high and leads to a continuous increase in the average length of the arrival queues. By comparison, flights at European airports are scheduled at a far more sustainable level than at US airports, as indicated by the fact that there is no steady increase of the hourly average delays during the course of the day, and delays are overall significantly more reasonable. It seems that the slot-control policies in Europe are preventing the queues from building up for the greater part of the day.
7.3 Europe and US individual airports’ performance

The fact, established in Section 7.2, that arrival delays are on average higher at US airports than at European airports is a first point of comparison between the two airport systems. A second point of comparison is motivated by Figure 17 which indicated that the evolution of delays over the course of the day in the US shows a steady increase from 7 am until 9 pm, while in Europe, the hourly average delays were more or less constant over that same period of time. We therefore investigate further the evolution of delays over a day as evidence of over-scheduling. We compare delays at a time when queues are the longest (typically in the late afternoon / early evening) to when queues are the shortest (in the morning).

Specifically, we estimated for each of the 68 airports of our study the difference between the “baseline hourly delay”, which is the minimum of all the hourly average delays between 7am and 10pm, and the “peak hourly delay”, which is the maximum of all the hourly average delays between 7 am and 10pm. As expected, the minimum level of delay in all cases is reached in the morning at 7, or 8 or 9 am, while the maximum is reached in the late afternoon / early evening, between 5 and 8 pm.

![Figure 18](image)

Figure 18 – London Heathrow’s hourly average arrival delays and span of the averages’ range

Two examples are provided in Figure 18 for London Heathrow and in Figure 19 for New York LaGuardia. At Heathrow, the minimum hourly delay occurs at 8am and the peak occurs at 6 pm, after which delays decrease considerably. At LaGuardia the delays are minimal at 7 am and peak at 7 pm, after which time they remain somewhat high. The difference between the minimum and the maximum – the range of the average delays during the day – is 11.8 minutes at Heathrow (Figure 18) and a much higher 30.6 minutes at LaGuardia. From the fact that the range is greater at La Guardia than at Heathrow, we conclude that LaGuardia airport suffered from greater over-scheduling and capacity-related delays than London Heathrow did over the year 2007. It is also very interesting in this comparison that average delay at London Heathrow is equal to 12 minutes as early as 7 am, when LaGuardia’s average hourly delay is only 3 minutes.
We repeated this analysis for the entire set of airports in Figure 20: for each airport we calculated the range of the hourly average delays, for every hour between 7 am and 9 pm. The results are presented in Figure 20. For example, the 3 top airports with the greatest delay increases are the 3 airports of the New York area: Newark (33-minute increase), LaGuardia (28-minute increase) and JFK (27-minute increase). At the bottom of the set, 3 European airports have very limited delay increase over the course of the day: Munich (4-minute increase), Paris-Orly (5-minute increase) and Berlin-Tegel (5-minute increase).

In a way similar to the aggregate picture in Figure 17, the individual European airports exhibit little variability in their hourly delay averages, and rank consistently lower than the American airports with respect to the range of the hourly average delays: of 68 airports, the 24 top positions are occupied by American airports, while the 19 bottom ones by European airports (Figure 20).

This study showcases a very clear difference between the US and European networks of airports, strengthening the findings of Section 7.2. US airports are over-scheduled, and as a result there is a large difference between the average delays in the morning and the average delay in the late afternoon. European airports, thanks to their demand management practices, are scheduled at a more sustainable level and enjoy individually a much reduced increase of their average hourly delays over the course of the day.
Figure 20 – range of the hourly average delays during the day at top US and Europe airports
7.4 Schedule reliability: standard deviation and distribution of delays

Schedule reliability at an airport can be thought of as the extent to which the actual time of arrival or departure of a flight adheres to the scheduled time. Schedule reliability captures a different dimension of airport performance than average delay. For example, if all flights were delayed by the same large amount of time, the average delay would be high but schedule reliability would be reasonable, since the actual times when a flight arrives or departs would be predictable. Conversely, the average delay might be small but, if many flights operated early and many others operated late, schedule reliability would be poor. (We are aware that, according to queuing theory, there is a strong positive correlation between average delay and schedule reliability, as measured by the standard deviation of delays.) Low schedule reliability, i.e., a large amount of uncertainty about actual flight times, has a major negative effect on the planning of passengers, on the amount of time they choose to spend at airports, on their ability to plan for and make their flight connections on multi-segment flights and, ultimately, on airline profitability.

We have quantified schedule reliability at the airports in our set by examining the probability distribution of delays and the standard deviations of delays. For every airport and for every hour of the day for which adequate data were available, we have computed the distribution of the arrival delay of flights, relative to scheduled time at the gate, for the entire year 2007. To this purpose we have calculated the fraction of aircraft that arrived between 0 and 1 minute later than scheduled, 1 and 2 minutes, and so on, for every 1-minute interval, in the range from 60 minutes ahead of schedule ("negative delay") to 240 minutes later than the scheduled time.

Figure 21 through Figure 28 present an example of these distributions for four different hours of the day for EWR and FRA. These distributions give a good indication of the reliability of the schedule at these two airports: if they are very "concentrated" (typically around the value of 0, but possibly around another positive or negative value) then the schedule is strongly adhered to and flights arrive near their "scheduled time plus the average delay". On the other hand, if the curve is not concentrated and the standard deviation of the delay is large, the flight schedule cannot be relied on, and the delays vary within a wide range of values.
Figure 21 – Delay distribution at Frankfurt airport in 2007, 8am

8:00 am – 8:59 am

<table>
<thead>
<tr>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 min</td>
<td>24.9 min</td>
</tr>
</tbody>
</table>

Figure 22 – Delay distribution at Frankfurt airport in 2007, 12pm

12:00 pm – 12:59 pm

<table>
<thead>
<tr>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 min</td>
<td>30.6 min</td>
</tr>
</tbody>
</table>
Figure 23 – Delay distribution at Frankfurt airport in 2007, 4pm

Average | Standard deviation
1.7 min   | 28.4 min

Figure 24 – Delay distribution at Frankfurt airport in 2007, 8pm

Average | Standard deviation
7.3 min   | 23.5 min
Figure 25 – Delay distribution at Newark airport in 2007, 8am

8:00 am – 8:59 am

<table>
<thead>
<tr>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 min</td>
<td>31.3 min</td>
</tr>
</tbody>
</table>

Figure 26 – Delay distribution at Newark airport in 2007, 12pm

12:00 pm – 12:59 pm

<table>
<thead>
<tr>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.3 min</td>
<td>41.3 min</td>
</tr>
</tbody>
</table>
Figure 27 – Delay distribution at Newark airport in 2007, 4pm

4:00 pm – 4:59 pm

<table>
<thead>
<tr>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.4 min</td>
<td>61.5 min</td>
</tr>
</tbody>
</table>

Figure 28 – Delay distribution at Newark airport in 2007, 8pm

8:00 pm – 8:59 pm

<table>
<thead>
<tr>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.4 min</td>
<td>57.9 min</td>
</tr>
</tbody>
</table>
In the case of Figures 21 through 28, one can immediately observe a striking difference between FRA and EWR. In the case of the former, both the average delay and the standard deviation of the delay remain relatively stable between 8 am and 8 pm; while for EWR, we observe a rapidly deteriorating situation as the day progresses. This example is typical of what we observed at other European and American airports. Specifically, our analysis of the delay distributions by time-of-day leads to the following quasi-general observations:

- in the US, over the course of the day, not only does the average delay increase steadily (as already indicated in Section 7.3), but also the distribution of the delay becomes increasingly dispersed – almost flat – suggesting a low reliability of schedule and poor predictability;

- in Europe, even at the busiest airports, the average delay remains relatively constant (as already indicated in Section 7.3) and the distribution of the delay reasonably concentrated over the course of the day, suggesting far greater reliability of the schedule. This is true even of London Heathrow, the airport experiencing the highest delays in Europe.

These observations support the hypothesis that a considerable number of US airports are “over-scheduled", notably those of the New York area and some of the most important hub airports. Moreover, they suggest that the airport system as a whole cannot sustain the current overall schedule of flights, building up delays and losing scheduling reliability over the course of an average day.

At European airports, the constancy of schedule reliability over the course of the day supports the hypothesis that most of them are scheduled at a level that is sustainable with respect to their capacities. This is corroborated by the fact the average hourly delay remains more or less stable from morning to evening at these airports.

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21 The number of flights in 2008 and 2009 has declined by a total of about 8% since its 2007 peak, but this may be only temporary relief.
7.5 Padding of block times

*Schedule padding* is the practice whereby airlines increase the scheduled gate-to-gate times, or “block times”, of flights in order to improve on-time performance. It is a natural consequence and reaction to the increase in average flight delays and the loss of schedule reliability noted above. We look briefly at schedule padding in the US and Europe, as it provides additional evidence of differences in performance between the airport systems of the two sides with respect to delays and schedule reliability.

The recent FAA/EUROCONTROL report (Enaud, Gulding, Hegendoerfer, Knorr, Rose, & Bonn, 2009) estimated that between 2000 and 2007, the average block time of intra-European flights remained constant. It was fluctuating only slightly according to season to account for winds and seasonal traffic levels. By contrast, it was found that the average block time for a domestic flight in the United States increased by about 3 minutes during the same period, with larger seasonal fluctuations. Equally important, an MIT study (El Alj, 2003) found that, between 1993 and 2000, the average block time for a large sample of flights increased by an average of 7 minutes. This indicates that block times in the US increased roughly by a total of 10 minutes between 1993 and 2007. The average domestic flight in the US is about 110 minutes long, therefore “padding” accounts for close to 10% of the average block time!

Stated differently, to improve schedule reliability in the face of long and highly variable airport delays, US airlines have been forced to increase over a period of 15 years certain important planned flight costs (such as the amount of crew time and aircraft time allocated to a typical flight) by about 10%.

Schedule padding is attracting considerable public interest in the US (McCartney, 2010) as airline passengers are increasingly noticing that they frequently arrive ahead of schedule, i.e., that airlines systematically allocate considerably more time to flights than would be needed in the absence of congestion. Our data analysis incidentally provides relevant evidence. In Figure 21, for example, a significant fraction of all flights at EWR arrive early (more than a majority). Similarly in Figure 25, an equally important number of flights arrive early. However, EWR has a higher proportion of very early flights (more than 30 minutes) than FRA at all the times of the day shown, despite the fact that average delay is much higher at EWR than at FRA from 4 to 5 pm and from 8 to 9 pm. A major reason for this is the large amount of padding typically assigned to US flights, particularly those to and from New York area airports. Moreover, at EWR, in the later hours of the day (Figure 26, Figure 27, Figure 28), as the average delays increase and the distribution gets more unpredictable, we also observe an increasing percentage of (very) early flights, that we did not see earlier (Figure 28) or at FRA (Figure 22, Figure 23, Figure 24). It seems that the schedule padding practice intensifies in the later parts of the day at EWR, and for that reason a greater percentage of (very) early flights is observed.

Practices of schedule padding tweak very directly the delay performances at airports. They will directly affect the average arrival delays relative to schedule (Sections 7.2 and 7.3). However the distribution of delays and their standard deviations (Section 7.4) will be more impervious to schedule padding, which affects the performance on the paper but not the schedule unreliability of the overall system.
8. Policy
The US and European networks of major airports and supporting ATM systems are equally advanced in terms of technologies in use, and quality of facilities and equipment. Important differences exist, however, in terms of operating procedures and scheduling practices. As a result, the two systems perform differently in important ways. Our study shows that neither system outperforms the other in every respect. In a nutshell, the comparison of the American and European systems of major airports constitutes a classical case of the trade-off between efficient utilization of the available infrastructure on the one hand, and level of service on the other. Moreover, the respective approaches and policies adopted by the two sides ultimately reflect different philosophical approaches to the management of air transport’s infrastructure. We will now summarize the differences in the current policies (Section 8.1), their impacts on airport performances (Section 8.1) and what policy recommendations these comparisons reveal (Section 0). We will also put these policies statements in the light of the differences in culture between the US and Europe (Section 0), and conclude on the needs for further research (Section 8.5) in order to strengthen the cases for policy changes that this study has brought up.

8.1 Summary of the differences in the present US and European air transport policies

8.1.1 Air traffic control
The most notable difference in air traffic control policies identified by our study is the frequent utilization in the US of visual separations between consecutive arrivals (see Section 4.1). VMC, which in theory imply the use of VFR, occurred between 63% and 100% of the time at the top 34 US airports in 2007 during daytime, with an average of 83% overall. Weather conditions that permit the use of visual separations are therefore much more frequent than IMC, which imply the use of radar separations (IFR) – the latter occur 17% of the time on average. European airports report using IFR exclusively, although it is possible that the radar separations are sometimes relaxed at some of the busiest ones – a form of VFR may exist at some European airports, in exceptional conditions. Such behaviors, if they exist would only be used to resolve temporary and extraordinary peaks in demand, and are not the norm.

Secondly, the United States, the United Kingdom and the other European countries apply different regulations for IFR operations (see Section 5.1), following recommendations by, respectively, the FAA, the CAA and the ICAO. These regulations are similar in essence, but include some differences in the definition of aircraft families and in several separation requirements:

- the FAA defines 4 aircraft families, the CAA defines 5, and the ICAO defines 3;
- the inter-arrival separation requirements vary within each of the regulations; the separation which is used most frequently in practice is 2.5 nautical miles in the US, and 3 nautical miles for the European countries;
- the inter-departure separation requirements vary as well; and
- the separation after a departure followed by an arrival is 2 nautical miles in the US, and 3 nautical miles or more in Europe.
8.1.2 Airport demand management

The major airports in Europe are slot-controlled. Different forms of slot controls exist (see Section 4.2); the most frequent ones are hourly caps for departures and arrivals separately; additional restrictions may exist for periods of time under 1 hour. About every six months (for the winter season and the summer season), the declared capacities are reevaluated and the slots are partially redistributed.

Declared capacities do not exist in the US, where any form of slot control is forbidden by law; the philosophy being that air transport should be open to all. Some limited exceptions (the High Density Rule) existed in the past for 5 airports, but have now expired. Generally, slot control and trading do not exist properly speaking at US airports.

Congestion pricing is another form of demand management policy. It is successfully set up at a few European airports (ex: Heathrow), but it is practically illegal in the US due the legislation over airports’ financing.

8.1.3 Delay management

In order to limit the extent of delays in the United States, the FAA designed the Ground Delay Programs (GDP). GDP are dynamic, real time, collaborative decision-making procedures between the FAA, airports and the airlines. Their objective is to control air traffic volume at airports where the projected traffic demand is expected to exceed the airport’s arrival capacity for a lengthy period of time. Most of the time, a GDP is triggered by a weather forecast for IMC at the destination airport. In practice, flights with a scheduled arrival at a GDP airport are assigned Controlled Departure Times (CDT), which are coordinated globally in order to reduce the arrival demand to the level of the airport’s reduced capacity (Federal Aviation Administration, 2005). GDPs can ultimately lead to cancellations, but overall, they are effective in preventing arrival queues in the air airports’ terminal areas; they can also diminish the propagation of delay.

The Central Flow Management Unit, EUROCONTROL, Brussels operates comparable policies for European flights, in cooperation with the concerned national Civil Aviation Authorities and airports. As mentioned in Section 4.1, airport capacity is less variable in Europe than in the US with respect to weather conditions and slot-control prevents at most airports excess demand peaks such as in the US; therefore, the action of the CFMU is less critical than that of the FAA’s GDP. For the same reasons, cancellations are less frequent in Europe than in the US.

22 The control of the FAA over demand management at these airports today is not clear, but certainly is not as extensive and systematic as in Europe.
8.2 Summary of the impacts of the policies on the performance of US and European airports

8.2.1 Airport capacities

The principal conclusion from the comparisons of airport capacities is that, due to the use of VFR procedures, weather permitting, US airports achieve much larger capacities than European airports with similar runway layouts. The use of VFR procedures at US airports leads to a 26% increase of overall airport capacity over the capacity that would have been achieved if IFR procedures were used all the time (see section 4.1). A second conclusion is that the FAA’s separation requirements for IFR operations are slightly more efficient than the ones used at European airports, and theoretically permit a capacity premium of the order of 10%, depending on the runway configuration (see Section 5.3). Thus, air traffic control practices and policies at US airports clearly result in a more efficient use of the infrastructure.

Going one step further, it was observed (see Section 5.3) that in comparison with other European airports or American airports, the declared capacities of some European airports are under-estimated, even when taking into account the less efficient ATC policies. We see here a possible effect of slot-control policies. At these airports, the power to declare capacities may not provide enough incentives to improve ATC practices; over time, the capacities of these airports may then remain low, while practices elsewhere are perfected. At the same time, many other European airports, among the busiest, declare capacities at a level matching (and sometimes exceeding) what might be expected of their runway layouts. UK NATS has some of the best practices in the world in this respect: it has managed at LHR and GTW to increase gradually the available capacities by improving practices. Declared capacities have been increasing at several other major European airports, as well, over the past years (e.g., CDG), as growing demand has required higher throughput rates. In conclusion, the negative impact of slot control on the efficient use of an airport’s infrastructure exists in some cases, but it is not systematic and does not appear at all at the busiest European airports.

8.2.2 Flight delays and schedule reliability

When it comes to level of service, the use of VFR procedures at US airports may lead to over-scheduling of flights. As a result, the on-time performance of an airport which finds itself in Instrumental Meteorological Conditions can deteriorate considerably, as the operational throughput is lowered from the VFR capacity to the IFR capacity. In 2007 in the US, flights arrived on average 9 minutes behind schedule in VMC and 23 minutes late in IMC\(^{23}\). The heavy reliance of US airports on the use of VFR procedures, and the subsequent airline scheduling with respect to the VFR capacities, makes them highly vulnerable to unacceptably long delays (and increased numbers of flight cancellations). On the contrary, by using IFR procedures all the time, and by scheduling with respect to declared capacities, the performance of European airports is less variable with weather conditions. In conclusion, air traffic control and demand management policies in Europe result in better delay performance at European airports.

\(^{23}\) At the top 34 US airports, averages include negative delays
Furthermore, it was shown that, even in VMC, delays increase steadily over the course of the day in the US, from 7am until 9pm. This suggests strongly that the existing flight schedules may have reached an unsustainable level, not only at individual airports, but also system-wide – at least for 2007, and maybe again in the near future. In contrast, European airports manage to maintain a roughly constant level of delay for most of the day, meaning that the slot controls are effective in protecting airports from excessive demand and sharp deterioration of schedule reliability. This hypothesis is corroborated by the study of delay distribution. In the US, uncertainty about arrival times increases over the course of a typical day. European airports are characterized by much more robust behavior: even when delays increase, the distribution of delays around their average value tends to remain “concentrated”, resulting in more reliable schedules.

8.2.3 Impact on airline economics

The higher capacities of the US airports and the absence of slot control may be offering some important economic advantages to the airline industry and to air travelers. The US domestic market is reputedly more competitive than the European one. One of the reasons is that it is easier for an airline to enter the market when access to airports is not restricted to slot-owners. Airlines also have greater freedom and flexibility to schedule the number of flights they want at the times they choose. This has some very clear consequences on airline strategies in the US market. Airlines in the US have been able to serve many markets at many different times of the day by operating smaller aircraft. This was done in order to increase the frequency of their service and thus gain market share. Indeed, it was calculated from Table 1 and Table 2 that the average number of passengers per flight at the top 34 airports in the US is 72, which is significantly lower than the average number of passengers per flight at the top 34 airports in Europe, 94 (difference: -23%).

The absence of slot control and other forms of demand management in the US may also have helped the development of hub and spoke operations, which typically require high capacities during peak times of the day at hub airports. Hub and spoke operations, the concept behind network configurations that rely heavily on connecting flights, allow airlines to decouple the number of markets they can serve, in order, again, to increase their market shares. In the US, the principal objection of airlines to slot control is their reluctance to having the government or other authorities interfere with their operations. Especially at a hub airport, where one airline is sometimes operating a large majority of the flights, that airline may justifiably fear that slot controls or slot auctioning may be harmful to their competitiveness and the efficiency of their scheduling.

Let us now advance a counter-argument to this line of reasoning. At near-capacity levels of demand (see Section 6.3, Figure 15), a reduction of a few movements only – which would typically come at a small or

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24 it is indeed proven theoretically and practically that, with the same total number of available seats, an airline will attract a greater market share by operating many flights with small aircraft at different times of the day, rather than by operating fewer flights with bigger aircraft journeys, thus providing fewer scheduling options (Belobaba, Odoni, & Barnhart, 2009)

25 Let it be noted that the average flight lengths are practically the same in the US and in Europe (Enaud, Gulding, Hegendoerfer, Knorr, Rose, & Bonn, 2009). Therefore, the difference in average aircraft size is not due to longer hauls in Europe, but indeed, to the marketing strategies of the airlines.
moderate cost to a subset of the airlines – can have a dramatic effect on delays – which certainly implies major benefits to the entire system. As was seen in the example of Figure 15, the total number of movements at Newark was not reduced by much over a typical day between 2007 and 2009, but delays declined greatly. This was accomplished through the removal or rescheduling of a few aircraft movements during peak hours when demand exceeded capacity. In other words, a capacity cap does not necessarily restrict the operations of airlines as they may often be able to re-schedule at little cost some of their movements away from peak hours, to less busy times of the day.

Let us now provide another example in support of the above point. We compare the schedules of two airports: one that is slot-controlled, Frankfurt, and one that is not, Newark. Newark and Frankfurt are two airports with roughly equally important regional and international roles, and they handle comparable numbers of aircraft and passengers. Both are major operational hubs, for Continental Airlines and Lufthansa, respectively. Incidentally, their runway layouts are somewhat similar and the capacities of the airports are comparable. However, their schedules for 2007 present strong differences.

Figure 29 shows the average number of scheduled movements per hour at Frankfurt; it shows that the schedule at Frankfurt is quite regular over the course of the day. At each hour, not only the total number of operations, but also the number of departures and arrivals separately remain roughly constant. Between 7:00 am and 21:59 pm, the average hourly schedule varies between 71 and 84 movements, with an average 77.2 movements per hour. The average number of hourly movements scheduled (77.2) amounts to 92% of the peak-hour schedule (84).
At Newark, by contrast (Figure 30), the total schedule is less regular and presents a clear, brief peak in the morning and a longer one in the afternoon. The separate schedules for departures and arrivals present an even greater variability: the scheduled number of departures falls by a factor of more than 2 between 8am and 10am! The average hourly schedule varies between 45.6 and 78.8 movements, with a global average of 65.3 movements. The average number of hourly movements scheduled (65.3) amounts to 83% of the peak-hour schedule (78.8).

![Figure 30 – Average hourly Schedule at Newark airport, 2007](image)

In conclusion, we observe that in the case of the Newark-Frankfurt comparison, slot control renders the schedule more regular, eliminating highly peaked profiles; this supports our earlier argument. If the regularity of the schedule at Frankfurt airport existed at Newark airport, then an additional 110 movements could be scheduled over the course of the day at Newark (an increase of 10%) while maintaining the peak schedule at 78.8 movements. These additional movements would take place at the hours when there is a schedule slack at Newark (for example between 9am and 12pm), and would therefore not affect delays by much.

Continental Airlines, which operates a hub at Newark airport, was a strong opponent of the slot auctions proposed by the FAA for EWR (Federal Aviation Administration, 2009). By comparison, most European airlines operate hubs at airports that are slot-controlled (BA at LHR, Air France at CDG, Lufthansa at FRA, etc.) – and do so successfully, at a level that is competitive internationally.
8.3 Policy recommendations

8.3.1 Recommendations for European Aviation Authorities and Airports

We first recommend that a number of European airports should re-evaluate their declared capacities, when it appears that the existing cap is underestimated. There is no clear reason for the sometimes large differences we observed in the capacities of airports with similar runway layouts within Europe. Even if demand does not critically require an increase in declared capacity at this time, it will be beneficial to offer the airlines greater flexibility in their schedule management by offering them additional capacity. This also encourages air traffic control to adopt better practices in preparation for a possible future growth in operations.

The ongoing effort to develop a pan-European level organization to coordinate air traffic management on a regional basis should be taken advantage of to harmonize airport capacity management across the continent. As stated earlier, some of the national agencies in Europe have implemented some of the best approaches in the world to increase air traffic control throughput. Their expertise in this respect could be critically helpful to other, less advanced agencies. Certainly, such collaborative efforts could be coordinated at the level of the newly created Single European Sky ATM Research (SESAR) program (EUROCONTROL, 2010).

We then recommend that the national Air Traffic Control providers study the possibility of authorizing visual separations (VFR), at European airports, weather permitting, with the goal of eventual implementing that measure. VFR procedures have been operated successfully and safely in the US for many years, and ATC at most busy European airports has the technology and the competence to operate VFR approaches equally well. The declared capacities need not necessarily be increased by the use of VFR. They can still be set with reference to the IFR capacities, so that the airports are not burdened with excessive demand and delays in bad weather conditions. The possibility to use VFR procedures would however give air traffic control more flexibility and greater means to address peaks of demand, and reduce overall delays.

Finally, we recommend that the radar-based separation requirements, in IFR procedures should be re-evaluated in Europe in light of the apparent advantages of the requirements in place at American airports. In particular, the separation requirement for a departure followed by an arrival should be scrutinized as it would seem that a 2 nautical mile separation is sufficient and safe in the US. These matters should be discussed with the ICAO, on whose separation requirements European airports rely for ATC operations. The discussions, here again, should be conducted at a European, rather than national, level.

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26 Some earlier efforts to improve and harmonize airport ATC performance across European countries include the work of EUROCONTROL’s Airside Capacity Enhancement team, which developed methodologies and offered assistance to European airports wishing to evaluate and maximize their capacity potential (EUROCONTROL, 2007).
8.3.2 Recommendations for the FAA and demand management at US airports

The performance of US airports with respect to airside capacity is commendable. The United States has led continuous efforts to improve air traffic control practices, while maintaining safety. It has achieved the most efficient flight processing procedures in the world, with the implementation of visual separations for arrivals. IFR operations are also handled most efficiently. Intensive research efforts are currently under way to improve even further air traffic control practices through the NEXTGEN project, which could increase airport capacities by double digit percentages.

At the same time, the United States has a policy of offering access to airports to all qualified operators, thereby forbidding any kind of demand management at the airport level. This has led to very high delays, in the face of limited capacities, and to a near-breakdown of the airport system at the peak of its utilization during the Summer of 2007. From the perspective of level of service, the United States has fallen behind most European airports and is at risk of a new round of record delays, if air traffic demand begins growing again at a fast pace.

The aversion of the United States to adopting airport demand management policies on a broad scale has undoubtedly been instrumental in stimulating the development of innovative ways for accommodating growing demand and achieving and maintaining high airside capacities. However, one must also acknowledge the fact that similar successes were possible in a few cases in Europe, at airports like London Heathrow, Frankfurt, London Gatwick, and Munich, where slot control policies have long been in force. It is therefore advisable for the FAA and the US Department of Transportation to review carefully their position regarding declaring capacities at airports where demand is clearly exceeding capacity for significant parts of the day and where airside capacity cannot possibly be improved further with the current infrastructure. This study has presented extensive proof that a cap on movements at such airports would be highly beneficial in terms of delay reduction with only small costs in terms of cuts in demand. In order to maintain the incentives to improve air traffic control practices and rules, the airports at which slot controls are implemented should be very carefully selected, based on both delay performance and theoretical capacity estimations.

The extensive use of VFR also raises some issues, in the sense that airlines in the US frequently schedule flights with reference to the capacity of airports under good weather conditions (“VFR capacity”). As shown in this thesis this may lead to unacceptable delays when weather conditions are less than ideal. Such measures as ground delay programs (GDP) are helpful in limiting the propagation of delays under unfavorable weather and should be encouraged. The fact remains that current US policies often lead to unsustainable levels of airport scheduling. If the use of declared capacities at some American airports ever were to become standard practice, both the VFR and IFR capacities of these airports should be taken into account. The cap on movements should be set to a weighted average of the two.
8.4 Different air transport cultures

8.4.1 American air transport culture and philosophy: free market and powerful airlines

Our policy recommendations for American need to be put under the perspective of the realities of the regulatory environment in the United States. The FAA has, as a matter of fact, already attempted several times to establish control over air traffic demand at, most notably, the three New York airports.

Through the so-called High Density Rule (HDR) the FAA had limits imposed on demand at the HDR airports of New York (JFK, LaGuardia, and Newark), as well as at Chicago O’Hare and Washington Reagan. However, Congress put an end to those controls on 5 April 2000, when it enacted the Wendell H. Ford Aviation and Investment Reform Act of the 21st Century (AIR-21), which phased out the HDR limits, effective 1 January 2007. As that deadline approached, and with traffic rising steadily at the time, the FAA attempted to maintain some control over the schedules at these airports, especially JFK and Newark. It put in place in 2007, the “Congestion Management Rule” for these 2 airports, which establishes caps of 81 movements per hour at both airports, and planned to implement it with the help of the first ever auctions of airport slots in the United States.

These auctions, however, never took place. The airlines challenged the legislative authority of the FAA to organize slot auctions and won their case in Federal Court. Eventually, the FAA rescinded the Congestion Management Rule (Federal Aviation Administration, 2008) (Federal Aviation Administration, 2009). Other examples of legal challenges to FAA’s efforts to implement demand management include the failure of implementing congestion charges at Boston Logan airport.

Airlines in the US are vehemently opposed to any demand management by the FAA as they believe that they are in a better position than the government to judge what is best for the overall air transportation system. The US legal system and general national philosophy have so far supported them. Our policy recommendations of the previous section may therefore be unlikely to be adopted, if coming solely from the FAA in the current regulatory environment. Enacting slot limits (or other demand management measures, such as congestion pricing) would require concerted support by the airlines and other major stakeholders, and a strong, high-level political will (meaning in Congress).

8.4.2 European air transport culture and philosophy: conservatism and powerful Civil Aviation Authorities

In contrast to the United States, airports have full authority in Europe to set capacities, in concert with the national Civil Aviation Authorities which set air traffic control policies. This arrangement has been instrumental, in some cases, in maintaining the same practices and declared capacities over many years, without incentives to change and improve. Furthermore, air traffic controller unions are quite powerful in Europe, much more so than in the US (where the massive firing of striking air traffic controllers by President Reagan in 1981 remains a landmark of the entire US labor history). In several European countries, ATC controller unions might be expected to oppose an increase of airport declared capacities and the use of visual separation procedures, weather permitting, on grounds of excessive workload and/or risk to safety.
In Europe, therefore, the challenge to implementing our policy recommendations to increase at some airports slot control and review separation requirements could be the opposition of the controllers’ unions. Significant tension already exists, as many national unions have expressed strong reservations about plans to consolidate air traffic services at the European level, fearing job losses.

8.4.3 Airline and flight delays information in the public domain

This thesis took full advantage of the data available in the public domain in the United States for all scheduled commercial flights. The extent and exhaustiveness of the information that airlines have to file with the government in the US provides an extremely rich database, which then allows for extensive analysis at universities or other research bodies, often with encouragement and support from the FAA itself. Such research is a major contributor to the effort to bring about best air traffic practices in the US and more generally to constantly check on and improve the efficiency of the overall system.

No equivalent to the US databases exists in Europe. The airlines there are much more protective of information related to their on-time performance. The most complete database, assembled by the CODA group at EUROCONTROL, works with airlines on a voluntary basis. The delay data shared by the airlines with CODA covers only less than 70% of all traffic in Europe. Furthermore, this database is not available in the public domain; only monthly summary reports are published by EUROCONTROL. This study received special permission to gain partial access to the database, but with a number of restrictions that limited the possibilities for analysis. It is strongly recommended that (a) submission to a central authority of detailed flight performance data be made mandatory for all major airlines in Europe and (b) this information be made available to researchers and other interested parties with reasonable restrictions.
8.5 Future research

This study tackled the general subjects of air traffic infrastructure and schedule management policies. It relied on a number of theoretical foundations that all deserve to be researched27:

- experimental capacity assessment, Pareto envelopes and airport capacity representation
- queuing theory and its application in modeling and forecasting airport delays
- airlines’ network and schedule management and the effect of slot control on it
- wake vortices and separation requirements

More specifically, it would be interesting to further this research by studying the theoretical representation of airport capacity. It has been mentioned several times in this report that an airport’s capacity, rather than being a fixed value, actually varies depending on weather, runway configurations, and even air traffic controllers’ efficiency. Therefore an airport’s capacity would be better represented by a probability distribution of capacity, rather than its average, maximum or any other rigid value. The subsequent policy making (delay and demand management) would gain in accuracy and realism.

It has also been mentioned in this study that the performance of an airport with respect to its potential over-scheduling and arrival queues is not necessarily best represented by the average of the arrival delays relative to schedule. These can be tweaked by the airlines through the device of schedule padding. We suggested, as one possibility, the alternative of analyzing the distribution of delays. More advanced methodologies could also be proposed in order to define the metrics that represent best the effects of over-scheduling at an airport (for example, the estimation of real-time demand for landings).

Last but not least, this research in its present state would not be sufficient to support the case of slot-control in the US, if it were seriously put up for political consideration. Additional work would be needed in order to establish a Cost-Benefit analysis, the only argument able to garner political support. Such study, in order to be realistic, would need to estimate the price of the fallouts of slot-control on the strategy and economics of airlines in the US, and the eventual cost to the US air transport customer. These considerations are extremely complex and vast, and for these reasons economic considerations were largely left out of the scope of this study, although some directions were hinted. Section 8.2.3 for example initiated the work that would be needed to assess the operational impact of slot controls on airlines’ scheduling strategies and profitability. The counterpart of this work would be the assessment of the benefits of reducing delays for the airlines operational costs.

Fundamentally, this study prepares a framework on which such a Cost and Benefit analysis could be based. It identifies the stakeholders and established methods to assess airport performance. It also offers the debate over slot-control in the US many empirical teachings that can be learnt from the performance of a comparable network of airports managed by different policies, the European network.

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27 They are as a matter of fact already researched intensely, at MIT for example.
Bibliography


