DEALING WITH AIRPORT CONGESTION:

DEVELOPMENT OF TACTICAL TOOLS FOR THE DEPARTURE FLOWS FROM A LARGE AIRPORT

by

BERTRAND DELCAIRE
Ingénieur Civil
École Nationale Supérieure des Mines de Paris, 1996

Submitted to the Technology and Policy Program

in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1998

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ABSTRACT

Research investigations outlined in this thesis deal with the problem of airport congestion and the policies that have been implemented by the Federal Aviation Administration in an effort to address it.

The policy and economics of air transportation do not allow for the exploration of various alternatives, but Decision Support Systems can be highly cost-effective solutions to improve airport capacity if properly designed. While various such tools have been designed to manage the arrival flow into a large airport, research on airport operations and tower dynamics shows a need for support on the departure side.

The underlying concept for a new decision support tool focusing on the tactical management of airport departure operations is outlined and its positive impact on congestion and Control Tower controllers' workload is reviewed. The major concept in this system can be found in the shift upstream of the decision to build specific departure sequences.

Although substantial work remains to be done before this concept can be transferred into practice, initial results not only support the development of such tools but also call policy-makers to further foster basic research on these areas.

Thesis supervisor: Professor Eric Feron
Title: Assistant Professor of Aeronautics and Astronautics

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- John Brandt, Flight Transportation Associates.

For their patience/tolerance/endurance/etc., to all my fellow students in my lab and in my beloved program.

I do not acknowledge Microsoft and Adobe for making the final printing of this document a nightmare (in case you wonder, the font is Book Antiqua).

This thesis was written during my spare time while I was publishing Christina Caloghirou's first opus, *Marketing the aesthetic encounter, the role of consumption in the design of the new Museum of Modern Art*, a title I will remember...

> *"Il vaut mieux penser le changement que changer le pansement."*
>
> *Francis Blanche*

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INTRODUCTION

Technological innovation in the Air Traffic Control system displays two challenges. First, because of the system's complexity and the interactions between many agents it involves, innovations often yield unexpected results. Second, it is almost impossible to evaluate projects prior to their implementation.[1] There can almost never be prototypes: since there is only one Air Traffic Control (ATC) system in the United States, coding of new en-route center display software must only be done once and correctly. On the other side of the coin, developing a system for a single facility (such as an airport) does not mean that it will be applicable to other facilities (other airports).

This does not however mean that everything is technical in the U.S. organization of Air Traffic Control. On the contrary, decisions always involve essential political values such as safety, equity and government efficiency. "A system straining at the seams of capacity is one that is also straining to be safe", according to the National Civil Aviation Review Commission. Similarly, work conditions of controllers and pilots have a key impact on the efficiency of the whole system. This situation puts policy makers (mainly the Federal Aviation Administration) in an awkward situation involving at the same time complex technologies, strong political and economic forces and controllers' concerns.

In this tight context, Air Traffic Control innovation follows a turbulent path. For instance, while airports are clearly identified as the key air transportation bottlenecks, the major initiatives recently launched such as ICAO's "Communications, Navigation, Surveillance/Air Traffic Management" concept (CNS/ATM) or FAA's flight 2000 ("path to free flight") do not propose substantial innovations to resolve this issue but rather focus on aircraft navigation technology. Similarly, satellite-based navigation systems have been given a lot of attention although the fundamental issue of their integratity seems very difficult to address.

This thesis attempts to cast light on tools that could meet all the requirements of innovation in the current National Airspace System. These tools are aimed at providing advice to controllers so that they deal more efficiently with the flows of traffic that they

---

[1] Unless a full 3D simulation tool is built, as happened at NASA Ames center recently. See Aviation Week, 11 May, 1998.

have to handle. In the framework of this research, the tools focus on the *departure flows from a large airport* such as Boston Logan International Airport.

The content of the thesis develops as follows. Chapter 1 frames the problem of airport congestion from a policy perspective. It outlines the sources of congestion, the users' incentives and the solutions that are currently implemented. Chapter 2 describes the current controllers' work environment, the available data in this environment, and the decision support tools that have been developed. These chapters justify the development of decision support tools that is undertaken in chapter 3.

CHAPTER 1

AIRPORT CONGESTION, A STRICTLY FRAMED PROBLEM

In this chapter, three perspectives on airport congestion[1] are presented to show how the current U.S. airport congestion policy is strictly framed by its stakeholders, which means that this problem can not be fully addressed at this moment. First, from the policy viewpoint, airport congestion does not lend itself to straightforward advocacy aiming for instance at larger federal investments in airport infrastructures. Then, the lack of a conclusive methodology to estimate the cost of delays reinforces this point and justifies why congestion pricing, which would stand as an obvious solution for economists, has not been implemented. Finally, current technological solutions implemented by the Federal Aviation Administration and airport authorities are reviewed in the final section.

1.1 AIRPORT CONGESTION: A FUNDING PROBLEM?

> *"Airline passengers are doomed to massive airport congestion and more dangerous skies unless the Federal Aviation Administration gets a radical overhaul, a government study said yesterday. The report by the National Civil Aviation Review Commission warned of a "looming disaster" of aviation gridlock that could set in soon after the year 2000 and damage the U.S. economy. The 21-member panel called on lawmakers and the White House to improve FAA management and finances. It urged a partial privatization of the agency and steps to shield aviation regulation from partisan budget battles. The proposed reforms would let the FAA beef up funding for the air traffic control system and airports to accommodate a rise in air traffic. [...] 'We'll have packed terminals, packed planes, packed skies and constant delays.' The world's air travelers are projected to double in number over the next 20 years, to more than 2 billion. The commission – made up of representatives from the aviation industry*

---

[1] In this thesis, airport congestion is limited to the so-called "airside" of large civil airports. The airside includes all movements of transport aircraft on and between airports.

> *and independent public members – also said a better-managed, better-funded FAA would make it easier for the agency to cut the rate of accidents.*
>
> *From* the Washington Post, *December 12, 1997*

The American National Airspace System (NAS) includes many components that are controlled by very different entities:

- The Federal Aviation Administration (FAA), both overseeing safety and in charge of the Air Traffic Control (ATC) infrastructure.
- Public authorities that own and manage most airports in the United States.
- Airlines, commercial corporations that provide travel service and control sections of the large airports.
- Aircraft and Air Traffic Control equipment manufacturers, that sell products to these three.
- Organized high-skilled professions such as pilots and air traffic controllers.
- Communities affected by air transportation because of either their location in the vicinity of an airport or their reliance on air transportation to remain linked to the rest of the country.

This diversity has generated the current organization, which integrates complex trade-offs between implemented technologies and the interests of these entities. Congress has held remarkably well its traditional role of resonance chamber for all these interests. At different moments,

- It introduced laws to protect consumers, opening markets to competition, forcing airlines to state how often their aircraft were late.
- It reacted to airport congestion, limiting demand at 4 major U.S. airports, creating a specific Airport Improvement Program, chastising the FAA for its inability to cope with traffic increase.
- It considered the hardships imposed on communities, including noise, pollution and limited service to small communities.
- It sympathized with the difficulties of the airline business, refraining from intervention in many antitrust and market power cases.

This succession of policies resulted in an unexpected growth of congestion. Flights are often late, airport operations are severely disrupted as soon as a storm strikes near an airport, and departing 70%-full aircraft wait in line before taking off from almost any large U.S. airport. While this situation seems self-explanatory, analysts' opinions differ strongly on the reasons underlying it.

1.1.1 The case for investments in new airport and ATC equipment

According to conventional wisdom, only clearly formulated policies convince American legislative bodies. Several propositions of this type have been made to solve the airport congestion problem. For instance, to expand airport capacity, PAYSON [1992] argues for airport privatization because "the current system suffers from an apparent shortage of capital to meet the airport system's future financing needs." The case that the system needs more funding is actually difficult to argue.

1.1.1.1 DEMONSTRATING THAT AIRPORT CONGESTION HAS INCREASED

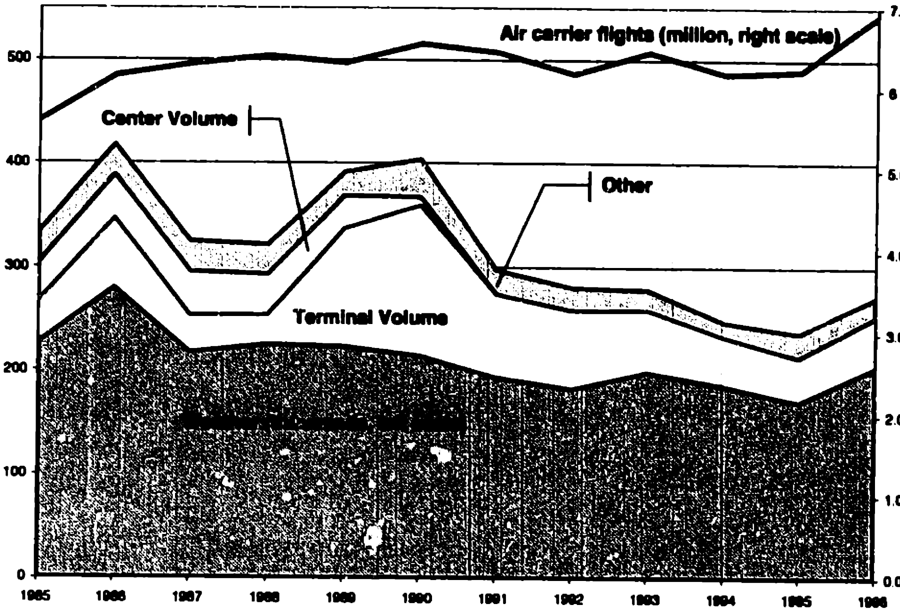
Demonstrating that airport congestion has increased in the last decades is a surprisingly difficult task to perform: the two official measures of this phenomenon do not provide clear results.

First, the FAA Air Traffic Service division implements the *Air Traffic Operations Management System* (ATOMS[2]), "in which FAA personnel record aircraft that are delayed in any stage of flight by 15 minutes or more by specific cause (weather, terminal volume, center volume, closed runways or taxiways, and NAS equipment interruptions). [...] A delay is recorded if an aircraft is delayed 15 minutes or more during taxi out or 15 minutes or more in any en-route center. Thus, an aircraft could be delayed 14 minutes during taxi out and 14 minutes in each ARTCC it passes through and not be recorded as a delay by ATOMS. Taxi-in delays are not counted."[3] This database is clearly designed to help identify the locus of *acute inefficiencies* within the ATC system. The evolution of the total number of aircraft recorded in this database, shown below on figure 1-1, is indeed inconclusive, decreasing from 330,000 flights in 1985 down to 270,000 in 1996.

---

[2] Also known as OPSNET or NAPRS.

[3] As is explained in the FAA-ASC [1996].



Sources: FAA ACE plans, 1992-1997. Note: In this database, a delay is caused by "center" or "terminal volume" when the controller judges that the flight was delayed because of the excessive traffic.

Figure 1-1: Number of aircraft recorded as delayed more than 15 minutes in the ATOMS database, by cause, 1985-1996

The second available database is the *Airline Service Quality Performance* (ASQP) that is used by the Department of Transportation to calculate on-time performances for the major carriers that are published monthly in the "Air Travel Consumer Reports". For every flight scheduled by one of the 10 largest domestic airline, the system records the scheduled departure, take-off, landing and arrival time, and the realized time of these events. These events are often called, respectively, "out", "off", "on" and "in".

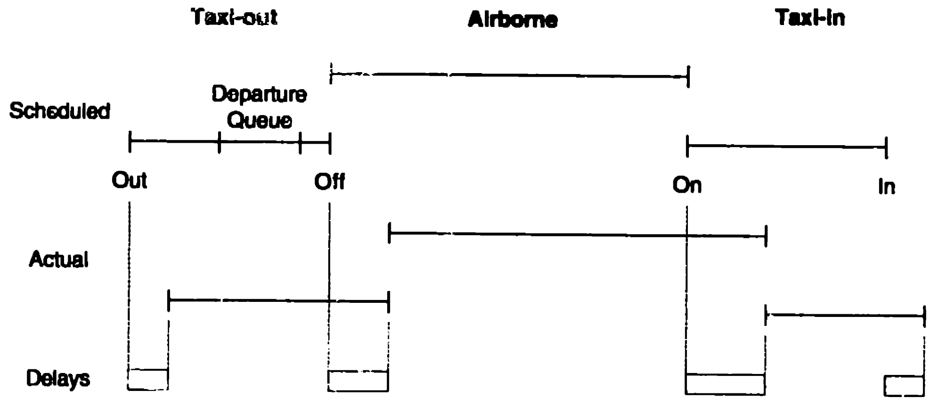
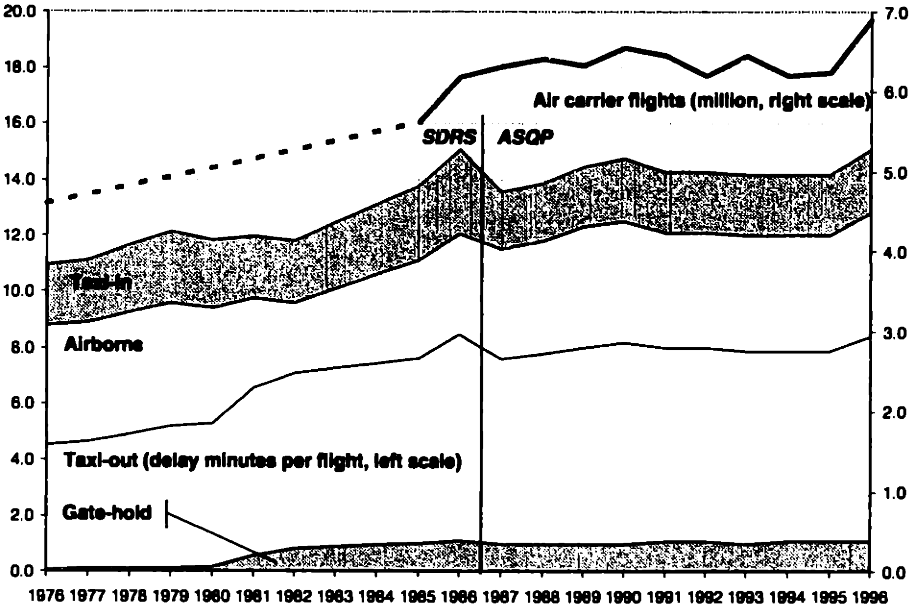


Figure 1-2: Scheduled and actual operations occurring during a flight

The delays recorded in the ASQP database are based on the scheduled departures and arrivals of each flight, as these have evolved over the years. When a flight arrives late every day, the airline soon decides to increase the scheduled travel time. This is why the evolution of the delays recorded in this system answer a very different question, namely the extent to which airlines' schedules are realistically calculated. It is thus not surprising that figure 1-3, based on this database, does not capture many noteworthy evolution of delays[4].



Source: FAA ACE plans, 1992-1997, OTA [1984], GEISINGER [1986]. Note: Data for 1983 and 1984 are extrapolated.

Figure 1-3: Evolution of average delays per flight recorded in the SDRS[5] and ASQP databases, 1976-1996

Fortunately, this database can be used to calculate a more appropriate measure of the congestion that plagues the system. The yearly average block time (from "out" to "in") between two airports can be extracted from all flights recorded in this database. The results for the main destinations from Logan Airport are the following:

---

[4] It is however easy to identify the implementation of "flow control" in 1982, which consists in holding aircraft at their gate (gate-hold) in order to reduce airborne delays. If an increase from 11 to 14 minutes delay per flight is apparent, the figures are stable between 1987 and 1996.

[5] The SDRS included only 3 airlines and was replaced by the ASQP in 1986. See section 1.2.1.2, p. 27.

Flights from Boston	Passengers	Block time			% increase
To	1995	1973	1994	1995	1994/73
LaGuardia	855,877	56.6	63.29	60.09	12%
Chicago O'Hare	739,914	149.2	159.68	154.38	7%
Newark	513,363	62.8	79.61	77.34	27%
Atlanta	509,495	149	158.6	158.88	6%
Philadelphia	494,350	69.4	79.31	77.52	14%
Washington National	462,767	78.3	95.64	93.36	22%
Dallas Fort Worth	433,574	227.8(1974)	244.12	243.67	7%

Sources: FAA [1976], T-100 reports and ASQP published data for 1994 and 1995.

Table 1-1: Evolution of average block times on selected segments from Logan Airport (minutes)

While these airports were already congested in 1974, the overall impact of 20 years of industry transformation has been a substantial increase of block time for the flights from Logan Airport to these major airports, notably Washington-National and Newark. This has happened while the fleets have maintained a relatively stable average cruise speed. However, the evolution between 1994 and 1995 shows that congestion is not increasing sharply in the current environment. The observed decrease can be due to many reasons, including weather and new Air Traffic Control procedures.

From the passenger point of view, the impact of this observation is even larger because flights with high load factor depart at peak hours and thus incur more delays: more passengers are on-board delayed flights.

As a consequence, generating the same amount of Available Seat Miles[6] takes today more time than in 1974 — or at least, does not take less time while most other industries work much faster. More than the exceptional delays that make headline news, this stagnation of productivity is the real impact of congestion on airlines and travelers.

1.1.1.2 AIRPORT INVESTMENTS DID NOT KEEP UP WITH TRAFFIC INCREASES

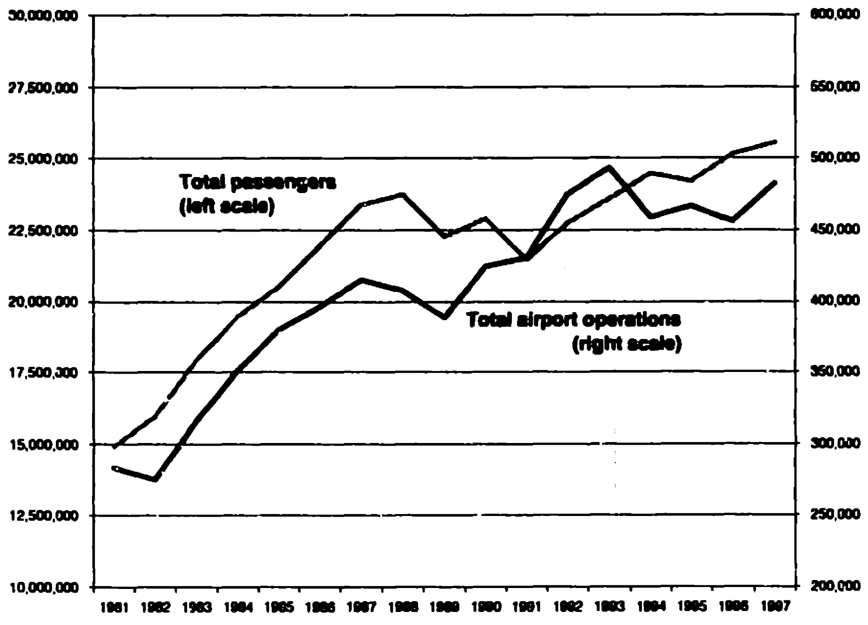
In parallel, very few airport airside investments have occurred in the last 20 years. Two new airports were inaugurated in the last 25 years, Dallas-Fort Worth and Denver International. Few runways have been built or extended. "What's needed is a burst of building on a grand scale."[7]

Traffic has grown substantially, as figure 1-4 makes it clear for Logan International Airport (on average 3.5% per year).

---

[6] Available Seat Miles (ASM) are a traditional measure of airlines' output; one ASM corresponds to the provision of one seat for one nautical mile.

[7] Quoted from Labich [1990].



Source: Massport traffic summaries.

Figure 1-4: Growth in operations and passengers at Logan Airport, 1981-1997

Considering the traditional representation of the relation between capacity, demand and delays shown on figure 1-5, congestion must occur.

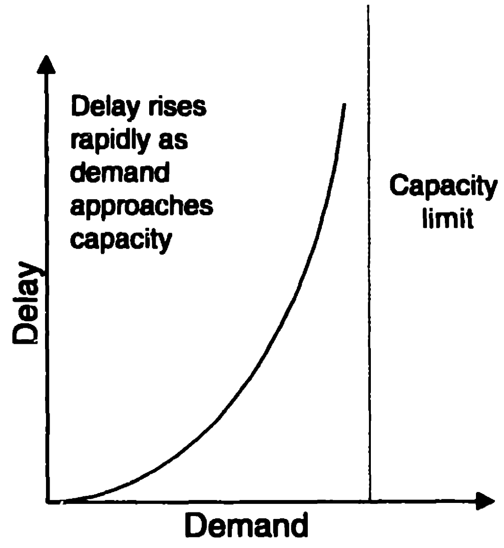


Figure 1-5: The non-linear link between capacity, demand and delays

The policy advocated on this ground is thus articulated in the following way:

- Since fares decrease thanks to deregulation, there is more demand for air travel.
- Airports and the FAA lack funding sources to invest in airport capacity to meet this demand. This explains why congestion grows.

- Thus, airports and ATC should be privatized.[8] Or, in the same vein, airports and the FAA must be authorized to leverage more funds, for instance through "passenger facility charges".[9]

1.1.2 The adaptation of airlines and Congress to the post-1978 deregulated environment

The discussion outlined in the previous section oversimplifies both sides of the congestion problem: the concept of airport capacity and the nature of the demand that is generated by airlines.

1.1.2.1 AIRLINES BEHAVIOR AGRAVATES CONGESTION

On the demand side, airlines play an important role in congestion. Following the principle of free competition, domestic airlines schedule their flights with total freedom except at four "high-density" airports. This gives the following results:

Airport	Total 1996 Passengers	Total 1996 Movements	Passengers Per Movement	
Chicago O'Hare International	69,153,528	909,593	76	US
Atlanta Hartsfield International	63,303,171	761,011	83	US
Dallas-Fort Worth Airport	58,034,503	848,028	68	US
Los Angeles International	57,974,559	763,866	76	US
London Heathrow	56,037,798	440,340	127	
Tokyo Haneda International	46,631,475	211,190	221	
San Francisco International	39,251,942	427,449	92	US
Frankfurt Rheim/Main	38,761,174	384,971	101	
Seoul Kimpo International	34,706,158	214,772	162	
Miami International	33,504,579	534,775	63	US
Denver International	32,296,174	444,698	73	US
Paris Charles De Gaulle	31,724,035	367,222	86	
New York J. F. Kennedy International	31,155,411	355,214	88	US
Detroit Metro Wayne County	30,610,993	538,424	57	US
Las Vegas McCarran International	30,459,965	476,511	64	US
Phoenix Sky Harbor International	30,411,852	526,648	58	US
Hong Kong International	30,212,327	176,843	171	
Newark International (New-York)	29,107,459	450,925	65	US
Minneapolis/St Paul International	28,771,750	485,480	59	US
Amsterdam Schiphol	27,794,873	342,603	81	

Source: Airport Council International web site, 1996.

Table 1-2: Total passengers, movements and average number of passengers per flight for the 20 largest commercial airports in the world in 1996

Among the twenty largest airports in the world ranked by passenger traffic, 13 are located in the United States. Except for Paris Charles-De-Gaulle and Amsterdam Schiphol, all non-U.S. airports carry on average more than 100 passengers per movement. This is not the

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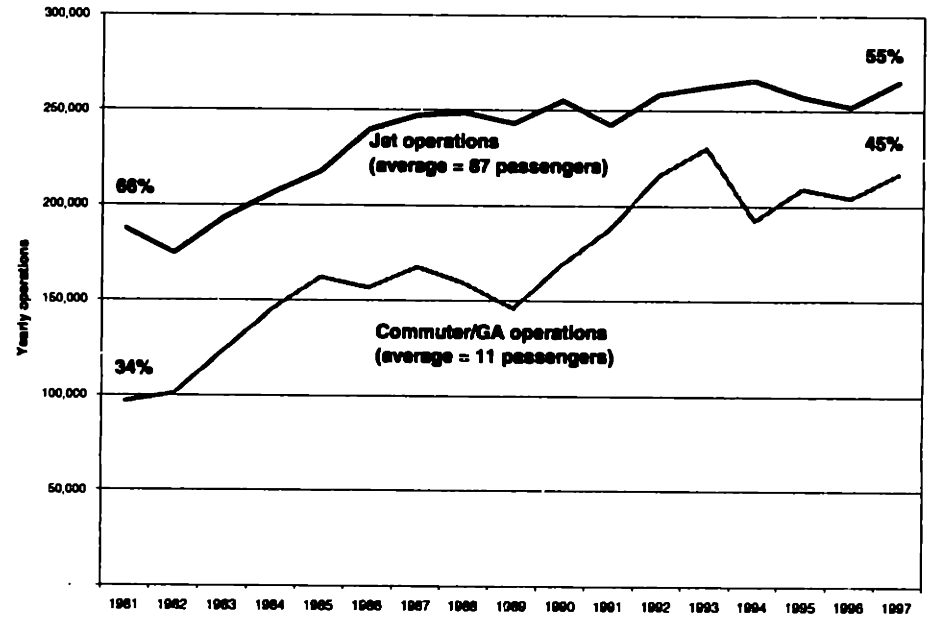
[8] See for instance PAYSON [1992] *Expanding airport capacity: getting privatization off the ground.*

[9] AIR TRANSPORT WORLD [1990] *Airport congestion got you down? Relief is spelled p-f-c.*

case for any of the American airports, including the supposedly restricted 4 "high-density airports".[10]

In details, during the second half of the 1980s, domestic airlines have heavily invested in regional aircraft in order to provide more frequent flights to business passengers on short-haul routes. On a July 1997 weekday, there were 39 scheduled flights from Boston to New York JFK, 39 to LaGuardia, 34 to Chicago O'Hare, 27 to Newark and 22 to Washington-National.[11] From the customer's point of view, this is indeed better service since a higher frequency reduces the so-called *schedule displacement* (that corresponds to the difference between the time the customer wishes to leave and the time a flight is actually scheduled to leave). For most passengers, this improvement is larger than the congestion it causes. This explains why demand at an airport like Logan Airport (Figure 1-6, below) has behaved in this way.[12]



Source: Massport monthly traffic summaries.

Figure 1-6: Yearly operations at Logan airport, split between jets and regional aircraft, 1981-1997

Similarly, since passengers prefer to fly at specific hours of the day, airlines schedule many departures during the so-called peak hours: early in the morning (7-9 a.m.) and during the late afternoon (5-8 p.m.).

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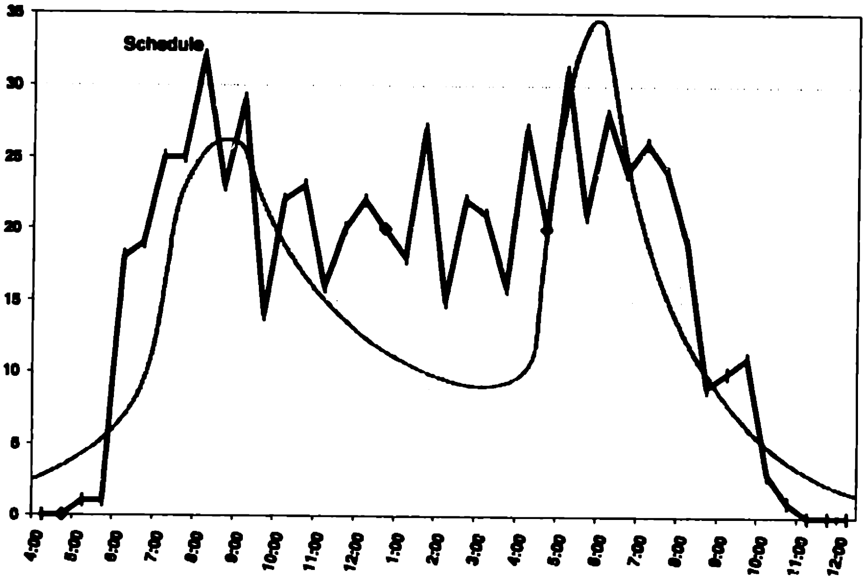
[10] Chicago O'Hare, New York LaGuardia and JFK and Ronald Reagan Washington National have been defined as such in 1969. This rule imposes a slot system to limit the number of IFR operations at the four airports. Since 1986, the FAA's final rule has allowed the sale of takeoff and landing slots. Newark has been recently dropped.

[11] For a total of 105 flights for the New York area, and 55 for Washington!

[12] HAMZAWI [1992] reports that "at Pearson International Airport in Toronto, commuter/feeder operations grew from 6% of the total air carrier aircraft movements in 1981 to 33% in 1989, while accounting for only a small fraction of the total passenger traffic — 2% in 1981 and 5% in 1989."

Figure 1-7 shows this clearly by superposing Logan schedule on a July day over a curve of passengers travel preference. The larger offer between 11 a.m. and 5 p.m. shows that airlines are forced to schedule flights at these less valuable hours, probably because of gate and airport congestion at peak hours.



Source: Official Airline Guide. In background, air travel demand as a function of time of day, as described by MILLER *[1972].*

Figure 1-7: Scheduled departures per 30-minute period from Logan Airport, 9 July 1997.

1.1.2.2 THE CONFUSING CONCEPT OF AIRPORT CAPACITY

On the capacity side, it is indeed difficult to determine if the FAA has not implemented the best possible policies[13]. Among other challenges, since 1981, the FAA has had to cope with President Reagan's firing of 11,000 air traffic controllers.

The separation standards that apply in the United States are the less stringent in the world, and were reduced to the point that some of them had to be subsequently increased for safety. These standards represent the major constraints on airport capacity. The difference in standards between countries typically means that an airport with the same layout has a much larger movements capacity if it is located in the United States than anywhere else in the world.

Unlike a stadium, in Air Traffic Control, pouring more concrete is not strictly equivalent to more capacity. Airport capacity is a stochastic variable that depends on a long list of factors that include the layout and equipment of the airport but also weather, aircraft mix, procedures and community restrictions like curfews. The ability to use this capacity is a

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[13] As suggested in OTA [1984], delays incurred by passengers in the terminals and during landside access are worse than on the airside, the sole area under the responsibility of the FAA.

function of the current and future demand and capacity of other potentially saturated elements of the NAS[14]. Handling congestion does not come down to simply "knowing how many planes the system can process, [something] FAA doesn't even know [...] except for four airports"[15].

Moreover, communities systematically scrutinize airport investments that may impact their noise environment. Airports do not have difficulties funding capacity-related investments. Their problem lies in finding *acceptable* investments.

1.1.2.3 AIRPORT CONGESTION POLICY CHANGES IN CONGRESS

As has been outlined in the previous sections, the problem of airport congestion has often retained the attention of Congressmen and, more generally, policy-makers.[16] However, the resolution of this problem can not be reduced to an airport-funding program such as the Airport Improvement Program (AIP).[17] This approach, which has been Congress' policy for many years, can be even further criticized because it amounts to Federal subsidies of the aviation industry, "providing abundant capacity at low cost to airport and airspace users"[18]. Landing fees are much lower in the U.S. than Europe or Japan. This was appropriate when air transportation was essentially a fledging industry that needed Federal support to deliver its full benefits to the U.S. economy. The question is: are these subsidies still needed? More precisely, since the provision of cheap air transportation, but not noise pollution, is in the public interest, how much Federal funding should be allocated to airports?

Articulating an efficient airport congestion policy neither comes down to complaining on the FAA's inadequate organization nor on its prehistoric computers.[19] It requires articulating an unpopular multi-level policy that would affect a long list of interests ranging from communities through businesses to the airline industry. Since this type of policy can not be acceptable to all stakeholders, Congress has resorted to piecemeal actions.

Government assessments published in the 1980s have repeatedly stated that the FAA was ill equipped to ensure safety and efficiency in a dynamic deregulated airline industry. Congress passed almost no statutory modifications in order for the FAA to cope with the changes in industry caused by the deregulation act of 1978. "Congress gave the FAA no more money, no more manpower, no new laws, and no new autonomy with which to

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[14] For instance, CHESLOW [1991] must develop complex simulations to determine the impact on national delays and throughput of a new airport in Denver.

[15] As an Air Transport Association (ATA) manager puts it in AIR TRANSPORT WORLD [1991].

[16] MAJONE [1993] provides a remarkable framework to analyze issues of policy changes. It requires considering a problem space, an actor space (the realm of politics) and a policy space (where ideas and actual policies are discussed). For a policy change not to occur, it simply needs to be unable to reach one of these three spaces.

[17] Whose funds are used very partially. Indeed, Congress has continuously debated whether large airports, that could almost be self-supported, needed Federal money (OTA [1984] p. 215).

[18] OTA [1984] p. 216.

[19] See for instance these two titles from the New-York Times: *FAA excoriated on failure to hire more air controllers* (June 13, 1997), *Air traffic snarled after third failure at a center on Long Island* (May 26, 1995)...

handle the exponential increase on work load that deregulation was about to unleash" (NANCE [1989]).

In general, Congress considered that the FAA could simply become a police that would put fines and revoke certificates. Indeed, Congress has only modified enforcement regulations in the 1980s; it neglected the necessary deep collaboration between the FAA and the aviation community without which none of FAA's goals can be achieved.[20] It procured the FAA billions of dollars for its modernization program, but never equipped it with the necessary institutional tools to manage this modernization correctly. On the main reforms suggested during the 1980s, Congress has the following record:

- **Suppression of FAA's mandate to promote industry**: finally in 1996, mainly for budgetary reasons. Was part of Rep. Burton subcommittee's recommendations that was created in the aftermath of the 1979 American Airlines DC-10 crash at Chicago O'Hare (HOFFMAN [1980]).
- **Creation of a government corporation to handle Air Traffic Control**: suggested again without success by the Clinton administration in 1994.
- **Appropriation for more inspectors to handle startup airlines**: increase in the Airline Deregulation Act of 1978 (300 more inspectors), then decrease during the real flood of new entrants, and increase in 1986.[21] The number of inspectors per operator fell from 4 in 1978 to about 1.5 in 1985.
- **Separation from the DoT (accused of limiting FAA action against industry):** proposed again without success in 1994.
- **Longer term for the Administrator:** 5-year term decided in 1994.
- **Long-term research plan and funding:** partially instituted in 1988, the R&D budget was however severely hit in 1997 (down to $115 million from $143 million in 1996[22]).The 1984-1987 period FAA administrator summed up this situation before the House Committee on Public Works and Transportation, Subcommittee on Aviation in May 1986:

> *"There has been change in the air transport segment of aviation brought on by deregulation. That change was not accommodated, perhaps not recognized, in the 1979 to 1983 time frame."*[23]

In conclusion, it appears that, since the airport congestion problem requires policies on multiple levels, policy-makers tackle it in a fragmented way, procuring new runways here

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[20] Which is now slowly rediscovered. See the SMA (p. 80) and CDM projects.

[21] OTA [1988] gives the following figures for the number of aviation safety inspectors:

1978	1980	1981	1982	1983	1984	1985	1986	1987
1,466	1,499	1,615	1,423	1,331	1,394	1,475	1,813	1,939

[22] These figures refer to the sole R&D budget, and not research funds within the Facilities and Equipment procurement funds.

[23] Quoted by MOSES and SAVAGE [1989]. This quote must also be read with reference to the too frequent change of administrators at the head of the FAA, and their non-supportive attitude towards their predecessors.

and there, helping the FAA to hire controllers for New York City, limiting demand at another airport.

However, they do not blame airlines for their inability to change their mode of operations to adapt to congestion. Is it in the public interest that airlines schedule 105 flights every day from Boston to the New York area? On the capacity side, while Congress suggests pouring more concrete on airports and billions on the Air Traffic Control modernization program, it seems that it has not given its Federal Aviation Administration the means to cope with the surge of traffic that followed the 1978 deregulation.

1.2 THE DOLLAR IMPACT OF DELAYS

Estimating the cost impact of a nuisance is a standard method in order to identify ways to deal with it. It is also an efficient way to mobilize stakeholders. Minimizing the cost of delays is a reasonable objective when exploring solutions to this problem. On this point also, the complexity of airport operations makes it difficult to develop valid methodologies. To demonstrate this, three methods used by the FAA and airlines to calculate the cost of delays are presented in this section:

(1) The methodology used by the FAA office of system capacity,
(2) The most-quoted "10 billion dollar" calculation from the FAA office of aviation policy and plans and,
(3) A spreadsheet developed by the financial department of a major airline.

The second section examines how airlines schedule their flights and the extent to which congestion has led to a change in their behavior. Since airlines have not adapted, economists have proposed a solution (congestion pricing) that is reviewed in the third section.

1.2.1 How delay costs are calculated in the literature

1.2.1.1 THE FAA OFFICE OF SYSTEM CAPACITY (ASC)

This office is working "to identify, develop, and implement initiatives that have the potential to increase the capacity of the national aviation system." It publishes annual reports on the capacity of the system and on the ways to enhance it ("Aviation Capacity Enhancement (ACE) Plans").

ACE plan year	Hours of airborne delay	Cost of delay
1992	1,800,000 (!)	$2.9 billion
1993	441,000	$706 million
1994	424,000	$678 million
1995	424,000	$678 million
1996	424,000	$678 million
1997	506,000	$809 million

Sources: ACE plans, 1992 to 1997.

Table 1-3: Hours and cost of delays published in recent ACE plans

The office of System Capacity builds its analysis on the two sources of data mentioned in section 1.1.1 (p. 15). The first source, ATOMS, does not give estimates of the overall weight of delays on the system since it only includes delays higher than 15 minutes.

This is the reason why, in order to estimate the total delays and their cost, the office uses the Airline Service Quality Performance database. Surprisingly, it only considers the average *airborne* delay. For 1995, the dollar estimate is then obtained by multiplying 4.1

minutes (average airborne delay obtained from the ASQP[24]) × 6.2 million commercial flights (1995) = 424,000 hours of airborne delay. At $1,600 per hour (the weighted average aircraft operating cost), this makes $678 million for 1995. To obtain $2.9 billion, the 1992 plan erroneously considers 4.3 minutes × $1,600 per hour × 26 million operations (1989). This last figure corresponds to *all* departures of aircraft, 20 million of them due to General Aviation... Airborne delay is a surprising measure since it is defined as shown below on figure 1-8. Not only does it use a subjective baseline (the scheduled airborne time considered by airlines), it also excludes delays during the taxi-out and taxi-in portions of each flight, which are the main impacts of airspace congestion.

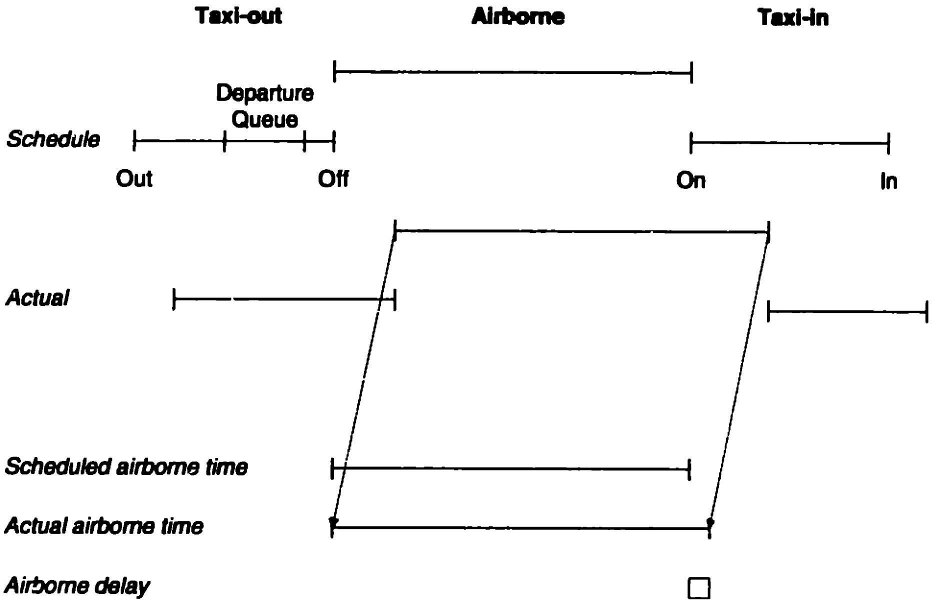

Figure 1-8: Definition of airborne delays

As expected, average airborne delays only show how airlines have been scheduling their operations: figure 1-3 (p. 17) shows that, in the last 10 years, they have scheduled the length of the airborne portions of their flights on average 4 minutes less than they actually took in the air. This measure and the cost estimates that are derived from it are not related to the capacity and demand within the National Airspace System.

1.2.1.2 THE FAA OFFICE OF AVIATION POLICY AND PLANS (API)

This office assists the FAA Administrator by developing policies, goals and priorities, by forecasting future aviation technology and demands and by analyzing the economic impact of regulations. In this context, limiting the cost (or the fuel impact) of delays is an important objective to monitor. In its history, this office has considered three modes of calculation.

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[24] This average delay is based on the ASQP sample that includes all domestic operations of the 10 largest U.S. airlines.

Until 1986, it published a yearly report entitled "Airline delay: 1976-19xx" that used the data obtained through the *Standardized Delay Reporting System (SDRS)*. Then, between 1987 and 1995, it updated a report entitled "Total cost for air carrier delay for the year 1987-19xx". Like the reports of the ASC described in the previous section, this report was based on the ASQP system, which replaced the SDRS in 1987. Finally, in the last few years, the office has tried to develop a more accurate reporting system named *Consolidated Operations and Delay Analysis System (CODAS)*. Since it has not yet published estimates of the cost of delays based on this new system, only the two first methods are reviewed in this section.

1. 1976-1986: AIRLINE DELAYS UNDER THE SDRS

The SDRS system considers only three carriers[25] that performed a total of 1.6 million flights in 1986. Based on the data from this system, these reports measure delays along different variables:

Item	1976	1986
Number of flights in the SDRS (1000)	1,419	1,576
Hours of delay: Total	258,991	396,670
ATC gate-hold	1,464	29,490
Taxi-out	105,396	193,091
Airborne	101,129	93,965
Taxi-in	51,002	80,124
Direct operating cost ($1000)		
Taxi-out	79,708	270,983
Airborne	101,621	214,496
Taxi-in	39,593	113,515
Fuel consumption (1000 gals): Total	228,455	262,611
ATC gate-hold	*Not in the SDRS*	*Not in the SDRS*
Taxi-out	53,650	86,491
Airborne	148,049	140,587
Taxi-in	26,755	35,533
Passenger hours (1000)	17,203	39,707

Source: GEISINGER *[1986].*

Table 1-4: Spreadsheet used by the FAA office of policy and plans to calculate the cost of delays before 1987

By looking at these different variables, the office is able to quantify the impact of FAA flow control, which consists in the transfer of delays from the air to the ground. This kind of aggregate policy evaluation is essential to the design of solutions to airport congestion, but is not captured by the methodology described in the previous paragraph.

The second part of this report develops a methodology to calculate the total delay cost for all air carriers. This method has been later used in the "total cost for air carrier delay" report that is examined in detail thereafter. Based on its figures, and after converting this

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[25] American, Eastern and United Airlines.

estimate in 1994 dollars, it gives an estimated delay cost of 3,225 millions 1994 dollars for 1976.

Interestingly, this report notes that the direct operating costs included are "only a fraction of the cost to the carriers. When serious delay problems develop, delay can propagate throughout the system. Flight departures are held for connecting departures on late-arriving aircraft. [...] Ultimately, additional aircraft, gates, and personnel must be available. In extreme cases, flights must be cancelled or diverted, resulting in a revenue loss, and passenger compensation must be provided." This caveat has since been forgotten.

2. 1987-1994: THE TOTAL COST FOR AIR CARRIER DELAY

This document details the following calculations:

Items (in 1994 $)	Source	1987	1990	1993	1994
1. Average hours of delay per flight	ASQP	0.228	0.248	0.239	0.237
2. No. of revenue flights (thousands)	DOT/BTS	6,373	6,572	6,825	7,095
3. Total delay (thousands of hours)	1 × 2	1,453	1,630	1,631	1,682
4. Aircraft operating cost ($/delay hr.)	DOT Form 41	1,686	1,954	1,571	1,495
5. Total operating cost ($ millions)	3 × 4	2,450	3,184	2,562	2,514
6. Revenue passengers/flight	DOT/BTS	94.1	92.2	92.6	94.8
7. Passenger delays (million pass. hrs.)	3 × 6	136.7	150.3	151	159.4
8. Value of passenger time ($/pass. hr.)	APO Report	44	44	44	44
9. Total passenger delay cost ($mil.)	7 × 8	6,015	6,613	6,644	7,014
10. Total delay cost ($ million)	5 + 9	8,465	9,798	9,206	9,528

Source: FAA-API [1995].

Table 1-5: Spreadsheet used by the FAA office of policy and plans to calculate the cost of delays after 1987

This mode of calculation calls for the following comments:

(1) The total delay in the system is obtained by applying to all revenue flights the average delay collected by the *Airline Service Quality Performance* system (ASQP) for the flights of the ten largest carriers. We may argue that other airlines do not face the same amount of delay per flight as they fly into less crowded airports.[26]

(2) The cost of delays to airlines is simply calculated as the product of the hourly operating cost by the total delay hours. These averages hide the differences between the different types of delays: at gate, during taxi-out, airborne and during taxi-in. These differences were taken into account before 1987 since GEISINGER [1986] clearly pointed that it is much cheaper to wait on the ground than in the air.

(3) This calculation of passenger delays considers only the delays that are reported in the ASQP system. Their baseline (scheduled block time) is as misleading as in the method outlined in the previous section.

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[26] This argument could also be made at the change from SDRS to ASQP.

(4) Finally, there is not much to say about the value of passenger time except that it should at least increase with the cost of living.

To make matters worse, a simple analysis of this method shows that *the biggest and most quoted figure on the cost of delays* is wrong. The report applies the average load for the major carriers that participate in the ASQP (line #6) to all domestic revenue flights (line #2). It is obvious that other airlines have smaller aircraft and thus carry much smaller loads. When multiplying the number of revenue flights by this average load, we obtain 672 million passenger emplanements, which is much more than can be found in the statistics (~501 million for 1994[27]). The corrected calculation would reduce the total cost of delays from $ 9.5 billion to $ 7.7 billion, a 20% reduction!

1.2.1.3 THE AIRLINES' APPROACH

Airlines follow a managerial approach to the issue of delay cost: what are the variables under their control to reduce the delays they face in their operations? Two sources are reviewed here to clarify this approach:

(1) An article published in an academic journal analyzing the performance of a decision-support system (RAKSHIT [1996]), and

(2) A confidential spreadsheet used by an airline to examine the value of investments to reduce delays.

The first article presents a decision-support system called "System Operations Advisor" (SOA) that helps aircraft dispatchers at United Airlines identify the best "delay and swap" solutions when operations get delayed. This typically happens when an aircraft must be kept on ground for unscheduled maintenance. The SOA suggests alternative solutions and shows the trade-off they impose between number of passengers delayed, amount of delay and number of misconnected passengers involved. Thanks to these delays and swaps, the SOA allowed the *saving of more than 27,000 minutes of potential delays.* "Using a conservative value of $20 per minute of delay", this has translated into $540,000 savings in a six-month period.

As expected from an airline, the designers of this system pick the costs and the customers involved as indicators of the performance of their SOA. These indicators are measured respectively by the number of *delay minutes* and the number of *delay passenger minutes* incurred if an alternative is selected. Their savings estimates are however simply based on a value of $20 per aircraft per delay minute. This later figure relates to the "$20 to $40" rule of thumb used as an average flight operating cost per minute ($1,200 to $2,400 per hour).

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[27] According to the BTS-FAA Airport Activity Statistics of Certificated Route Air Carriers.

The second document is an attempt to calculate the average cost of a *departure* delay for an airline. This confidential document was issued by the financial analysis division of a major airline. It takes into account the complex variation of some delay costs with the length of delay. Table 1-6 below illustrates this methodology.

Item	Definition	Evolution
Meltaway cost	Revenue lost on business passengers walking away	Saturates when all business passengers have walked away
Misconnect cost	Cost caused by the misconnection: rebooking (eventually on another airline), cancellation, accommodation	Probability of misconnection saturates at 100% when delays are too large
Mishandled bag cost	Similar	Higher when the departure delay is between 15 and 45 minutes
Crew cost	Extra labor cost (paid by the minute)	The pilot will often speed up to reduce the departure delay
Fuel costs	Both sitting at the gate and speed-up cost	Speed-up is economical!

Source: Airline financial analysis division.

Table 1-6: List of delay costs considered by an airline financial analysis division

It is important to note that misconnections and meltaway costs are the largest items in this list. Crew costs become important only after large delays. This means that airlines are first and foremost concerned with the potential impact of delays on these first two costs. The summation of these 5 items builds a complex non-linear delay cost function.

By departure delay, this analysis considers the delay that occurs prior to the "out" event. At this point, business passengers have the opportunity to walk away to another airline. Yet, they will do so only if the delay does not affect competitors. Once the doors are closed, this cost must not be compounded since business passengers no longer have the choice to walk away to another airline. Only the four other costs remain. However, misconnection and mishandled bags cost only if the delay has not been scheduled. This means that delays have very different costs for an airline depending when and how they occur.

Type of delay	Prior to "out"	"Out" to "in"
Included in schedule	Crew Fuel	Crew Fuel
Unexpected Applying to all airlines (for instance: weather)	Misconnection Mishandled bags Crew Fuel	Misconnection Mishandled bags Crew Fuel
Unexpected Applying only to this airline	Meltaway Misconnection Mishandled bags Crew Fuel	Very rare

Table 1-7: The different types of delays that affect airlines

This airline financial analysis division considers only the shaded cell in table 1-7. It corresponds to delays against which the airline can *a priori* do something. Delays that systematically occur, for instance when a flight is scheduled to depart from a congested airport at peak hours, are included in the schedules and only require more crew time and fuel.

This difference explains why airlines put an emphasis on the respect of the *departure* schedule while the FAA considers the overall delay "in the system". As long as aircraft depart relatively on time, airlines are fine since travelers must stay with them! Routine ATC delays are included in the schedules and are equivalent to a decision to serve airports that "move away from each other". Airlines' concern with delays is thus rather ranked as follows:

(1) Reducing unexpected delays affecting only the airline's operations prior to pushback. By construction, these delays are almost only caused by the airline's own organization[28].

(2) Reducing unexpected delays affecting all airlines, i.e. abrupt variations in capacity (mainly because of weather and Air Traffic Management decisions[29]). The FAA is responsible[30] for these delays, for instance because of its limited ability to operate an airport safely under poor weather conditions.

(3) Reducing routine delays that impact all operations. Airports and the FAA are responsible for these[29].

Finally, although the SOA shows the difference between large and small aircraft (through the number of passengers involved), the confidential spreadsheet does not compute the large difference in delay cost between a large aircraft and a small one. It should however be clear that delaying a large aircraft or one that connects with many other flights is much more costly.

Table 1-8 closes this review of the cost impact of delays on domestic air transportation. It shows, as noticed, that the FAA has published substantially different estimates based on the questionable ASQP delays. It indicates also the estimate calculated by the Air Transport Association (ATA) that represents the largest domestic airlines. None of these estimates appears convincing because they all rely on scheduled durations, either from the ASQP database or from other sources (the great circle mileage divided by 7 miles per minute for ATA estimates of nominal airborne times).

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[28] Including the choice of aircraft and crews that can not fly under all weather conditions. See appendix 4.5 p. 136 for delay causes prior to pushback.

[29] We use this term to refer to Air Traffic Flow Management (ATFM) decisions that suddenly impact operations bound for a given airport, like Ground Delay Programs (GDP). These practices are discussed in chapter 2, p. 53.

[30] Here, "responsible" means that the FAA (and airports for item 3) takes (or does not take) the decisions that result in these delays, however obvious they are. Airlines have recently discovered that they could actually help the FAA take better decisions (Collaborative Decision-Making), but the agency remains in control of these delays.

In the end, the examination of the way an airline calculates *departure* delay costs has revealed that airlines are more concerned with the impact of delays on loss of revenue than on their direct operating costs, which translates in a different cost for each type of delay.

Source	**Estimate**$^{(\text{year},\ \$\text{ year})}$	**Comments**
FAA-ASC	$\$2.9\text{ B}^{(1989,\ 1989\$)}$	Error.
FAA-ASC	$\$0.7\text{ B}^{(1995,\ 1995\$)}$	Only airborne delays based on the surprisingly stable 4.1 minutes per flight of the ASQP.
FAA-API	$\$3.2\text{ B}^{(1976,\ 1994\$)}$	Based on the SDRS system delay (11 minutes in 1976), probably making the same mistakes (with a lower impact) as the studies that followed up.
FAA-API	$\$7.7\text{ B}^{(1994,\ 1994\$)}$	Total cost (including passengers) based on the total delay per flight from the ASQP, *corrected*. This figure remains far from the "10 billion dollar" often quoted.
FAA-API	$\$2.5\text{ B}^{(1994,\ 1994\$)}$	Airline operating costs only.
ATA	$\$1.5\text{ B}^{(1996,\ 1996\$)}$	Spreadsheet published by the Air Transport Association: ATC delay costs incurred by 16 largest domestic airlines.
ATA	$\$\ 3.3\text{ B}^{(1996,\ 1996\$)}$	Spreadsheet published by the Air Transport Association: total ATC delay costs, including $840M for ground costs and $1.5B for passenger costs.

Table 1-8: Summary of recent estimates of the cost of delays

1.2.2 Airline scheduling and congestion pricing

The previous section has presented a fundamental cleavage between the delay costs that airlines try to control and what the FAA may consider as indicators of its ability to meet the schedules of its users.

This probably comes from a misunderstanding of the purpose of airline scheduling. In turn, it explains why major U.S. airlines have apparently not tried to modify their scheduling practice to ease congestion, and why they strongly oppose economic restrictions on demand. These three points are reviewed now.

1.2.2.1 THE VARIABILITY OF AIRLINE OPERATIONS

In competitive manufacturing industries, productivity gains, typically measured in minutes to produce a part, are often of the order of 5 to 10% per year. Lean production, Just-In-Time and similar buzzwords have focused these companies on their hourly productivity. On the opposite, as shown for Logan Airport on table 1-1 (p. 18), the airline industry has not achieved significant productivity gains in recent years.[31]

To progress on this issue, it is necessary to look more precisely at the distribution of out-to-in times[32] for some segments. Beside an increase in the average time needed to provide service between two destinations, it appears that the current congestion adds to the

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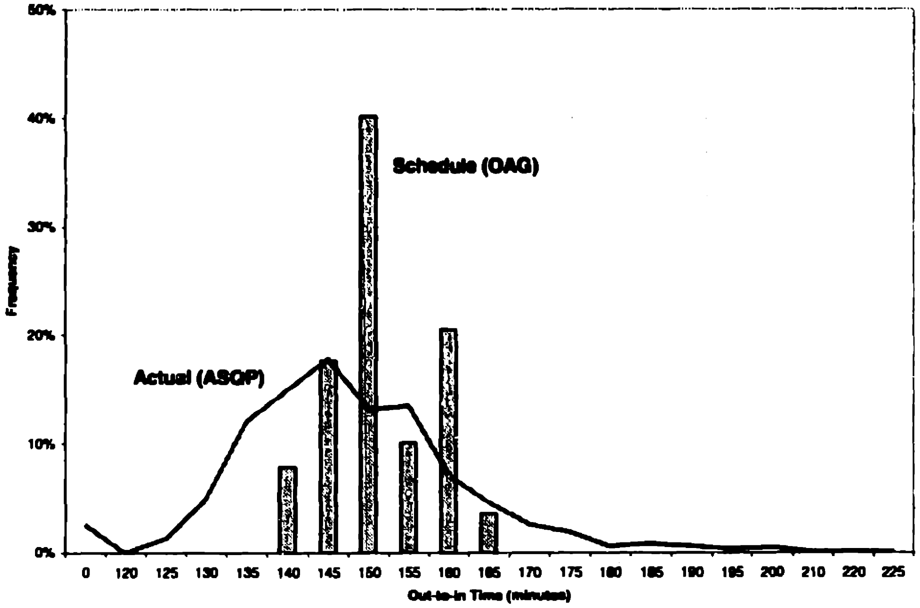
[31] Although it may show a remarkable increase in productivity *per employee*.

[32] "out" and "in" events are defined on figure 1-2, p. 16.

natural variability of travel time. It is however important to remember that airlines are not railways; weather conditions are probably the major cause of variations in travel time.[33]

The following figure 1-9 shows clearly this variability. It is based on 840 flights flown from Boston to Chicago in September 1995 and recorded in the ASQP database.



Source: ASQP database for September 1995, 840 flights.
Figure 1-9: Variability of out-to-in time for flights between Logan Airport and Chicago O'Hare

This distribution must be compared to the scheduled out-to-in times that are published in the Official Airline Guide (bars), contained between 142 and 165 minutes. This pattern is found on all segments examined, the standard deviation increasing with the stage length. For instance, all flights Boston-Atlanta (figure 1-10) have an OAG out-to-in time between 149 and 156 minutes (showed as the bars on the histogram), yet they take between 130 and 180 minutes.

This variability is generalized for all airline operations. Thus, the only way to control the air transportation "production process time" is to build margins in the schedule. To achieve a 91% on-time departure performance[34], airline employees start preparing flights earlier and earlier, and, as a result, some flights end up leaving before their schedule, as shown on the figure 1-11 below for Boston.

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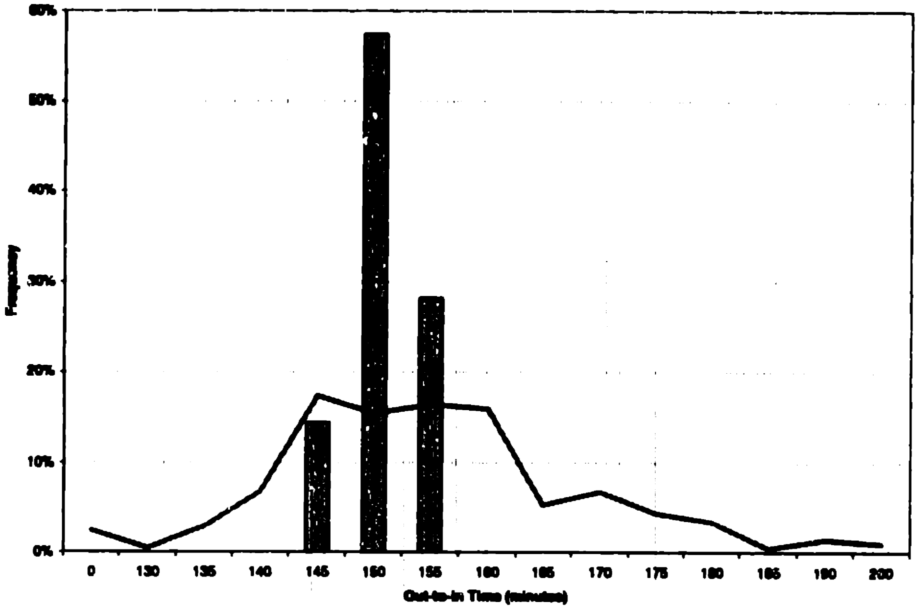
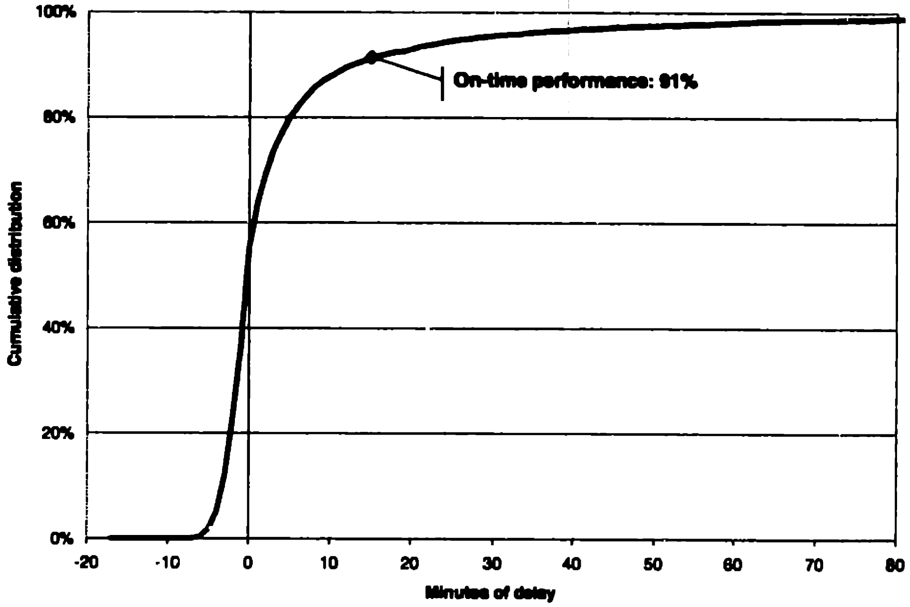
[33] The respective variance of "block-to-block" times and airborne times are not extremely different.

[34] This on-time performance is published by the DOT in their Air Travel Consumer Report and defined as the percentage of flights departing with less than 15 minutes delay on their published schedules.



Source: ASQP database for September 1995, 208 flights.
Figure 1-10: Variability of out-to-in time for flights between Logan Airport and Atlanta Hartsfield



Source: ASQP database for September 1995.
Figure 1-11: Difference between actual and scheduled out time for the departure flights from Logan Airport

Within a 'hub' logic, aircraft often wait for connecting passengers. This connection between flights does not accommodate well the variability of out-to-in times. This situation leads to a strategy based on long turnaround times and a goal of 70% flights on or before schedule (FLINT [1997]). An airline that operates without connections, like Southwest, can aim at a higher on-time departure performance and schedule shorter turnaround times. The departure times of its aircraft are independent from each other and the turnaround time is not used as a buffer. Simply stated, a hub-based schedule suffers more from out-to-in time variability than a point-to-point schedule. It is interesting to note that some scholars have analyzed this difference by a contrast in organizational behavior, under the assumption that short turnaround times were focusing personnel towards on-time performance while long turnaround times would give them time to waste[35].

Without entering into the details of airline scheduling methods, it is important to mention that schedules are not fully optimized. Rather, an airline integrates the following concerns:

- It focuses only on potential *changes* to the current schedule, that is based on a long history of business decisions.
- It thinks in terms of tolerability of delays: an airline modifies a schedule only when its operational staff considers the delays intolerable or proves that there are gate compatibility problems. Scheduling is a marketing task.
- Competition from other airlines: airlines have mixed incentives to schedule similar flights at the same time as other airlines. On the one hand, it allows head-to-head competition. On the other hand, if traffic flow management procedures are necessary, the delayed aircraft incurs more extensive delays.[36]

1.2.2.2 EVIDENCES OF SHIFTING STRATEGIES

In this section, evidence that airlines have (or have not) reacted to this trend in delays is examined to confirm that the scheduling process is performed without consideration for its congestion impact.

On the positive side, it is true that on-time performance has become a corporate objective for some airlines. Some carriers are willing to add more turnaround time margins, invest in coordination with Air Traffic Control, motivate and pay personnel on an on-time performance goal.

Second, airlines have been seeking hubs where they could be dominant. A recent example of this behavior was given by Delta's development of a hub at CVG (Cincinnati) where delays and ground costs are lower than in Chicago (REINGOLD [1995]). The number of dominant hubs has increased from 4 to 8 between 1990 and 1995.[37] This search for

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[35] See GITTEL [1995].

[36] A famous case of adaptation (collusion?) is given by the fact that, in two-airline hubs such as Chicago, banks of each airline are offset from each other. Otherwise, flights could be extremely delayed.

[37] If a dominant hub is defined as one where the No. 1 airline has a market share higher than 50% and the No. 2 airline has less than 10%, according to data published in Air Transport World in November 1996.

dominance is being justified by lower ground costs, as was shown in BANKER [1993], a remarkable accounting analysis of the cost drivers in the US airline industry. This study showed cost savings from hub dominance. The exact source of these savings remains unclear. Among others, it may be the ability of airlines to better schedule their flights in and out of such an airport.

Yet, in spite of these few positive examples, delays have not forced airlines to make substantial modifications to their strategies. Despite FAA's report to Congress on *potential new connecting hubs* (FAA [1991]) or articles advocating more balance between airports (HAMLIN [1989]), airlines continue to have their hubs at the most congested airports. They complain that ground costs "have run out of control" (AVIATION WEEK [1992]). They save on spare aircraft, which can have a tremendous effect on cancellations[38], and so on.

On a more global level, airlines have many reasons not to adapt. First, delays affect them all without large differences: on-time performances are comprised between 76% and 82% for all 10 "major air carriers"[39]. As discussed in section 1.2.1.3 (p. 30), they consider that the FAA is the source of all these inefficiencies (AVIATION WEEK [1995]) and that there is not much to do. Second, the competitive environment forces airlines to look for revenues wherever they can find them. Peak-hour flights generate revenues that far outweigh the induced congestion costs. Since frequency of service is essential, airlines invest in regional aircraft that aggravate congestion. Third, whatever the level of congestion is, air transportation's competitors remain much slower. Finally, crew compensation is based on block hours. For them, shorter flights would mean "flying more segments for the same wages". While their wages are already under strong pressure, pilots are thus not motivated by this objective.

In any case, resource constraints are now felt at the level of each airport. Some station managers already had to negotiate changes in the peak season schedules because there would otherwise be more aircraft at the same time at the airport than they can actually accommodate.

1.2.2.3 THE ECONOMICS ANSWER: ALLOCATING A SCARCE RESOURCE

Economists have simple answers to congestion problems, which they view as problems of inefficient resources allocation methods. Following FAWCETT & FAWCETT [1988], the following methods may be considered:

(1) *Scheduling committees* that already exist at the high-density airports, but they favor incumbents and have not been very efficient in limiting congestion (*cf.* the delays at the airports that have implemented them).

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[38] A single spare B737 at a hub can avoid up to 1,000 cancellations per year.

[39] From the Air Travel Consumer Reports for 1995. This does not include the comments of CAULKINS [1993] on the pertinence of a comparison between airlines that do not fly into the same airports.

(2) *Lotteries*, usually considered as ***deadlock-breaking mechanisms***. Chance is however not efficient: the lotteries' scope is limited to protect incumbents and new entrants receive slots that they have difficulties to use.

(3) *Auctions*, but a slot is valuable only if you own a similar slot at a destination airport. Besides, auctions require more capital from new entrants.

(4) *Variable landing fees*: increase the price of air travel at peak times, and the flights that do not have a serious financial motivation to leave at peak hours will shift to off-peak times. Raising landing fees internalizes delay costs.

The fourth method has atttracted a lot of attention when it was implemented at Logan Airport under the name "Program for Airport Capacity Efficiency" (PACE). This project has however been considered illegal because of its impact on the equity of access to the airport, both for small communities and small users (General Aviation and commuters) and on competition between airlines.

Usually, the difficulty of such pricing schemes lies in the need to clearly evaluate the anticipated effects on the different users' behaviors: it may simply shift traffic peaks to other periods, for instance earlier in the morning and later at night, which may not please the surrounding communities. Again recently, BARRETT, MURPHY et al. [1993] proposed a fee mechanism for Logan Airport, but the situation remains stalled.

Since airport traffic increase, competition and the provision of service to small communities are still considered in the public interest[40] (unlike road traffic increase), these economic solutions have not been extended to airports beside the four high-density ones, and even on these airports, they have not reduced congestion.

Considering airline strategies outlined in section 1.2.2.2, the prospects for demand management methods are still weak. In conclusion, while delays appear to cost a lot, they are not sufficient to convince airlines to change their organization and Congress to take serious steps such as demand management. Congestion policies are locked on methods to increase airport capacity. **Higher airport capacity remains an important aviation policy objective in the United States.** We now investigate how this objective can be met.

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[40] Congestion has not yet changed policymakers' decisions to change this emplasis as CURTIS [1989] argued.

1.3 CURRENT SOLUTIONS TO AIRPORT CONGESTION

When it comes to the search for solutions to the problem of airport congestion, engineers easily provide long lists of approaches. For instance, HAMZAWI [1992] reviews the following options to balance airport capacity and demand:

Increase capacity	Build new airports
	Expand existing facilities
Reduce demand	Provide remote processing
	Develop super-hubs
	Pre-clear international arrivals
	Relocate certain traffic operations
	Shift short-haul traffic to other modes
Spread peaks	Peak period pricing
	Gate/Slot auctioning
	Traffic quotas and slot allocation
	Traffic flow control
	Restrictions on General Aviation
Technological and operational innovation	Apply technological innovations
	Adopt innovative operational practices

Source: HAMZAWI *[1992].*

Table 1-9: Options to balance airport capacity and demand

Considering the position of the main actors that was described in the previous sections, it is not surprising to notice that the practice of airport operations improvements is drawn from a much smaller set of solutions. This however does not mean that the aviation community, forged by a succession of exceptional technological achievements, has not contemplated *disruptive* innovations to solve the congestion problem.

1.3.1 The misfortunes of airport operations innovations

On the contrary, engineers are extremely creative when it comes to suggesting new concepts of airport operations that would greatly contribute to solve the airport congestion problem:

(1) **Aircraft technology**, including tilt-rotor aircraft, quieter engines and very high-capacity aircraft ("New Large Aircraft").

(2) **New airline organization**, around the concept of "wayport" and connecting hub airport, the transfer of some operations (General Aviation, shuttles) to secondary airports, the conversion of military airports into civilian facilities.

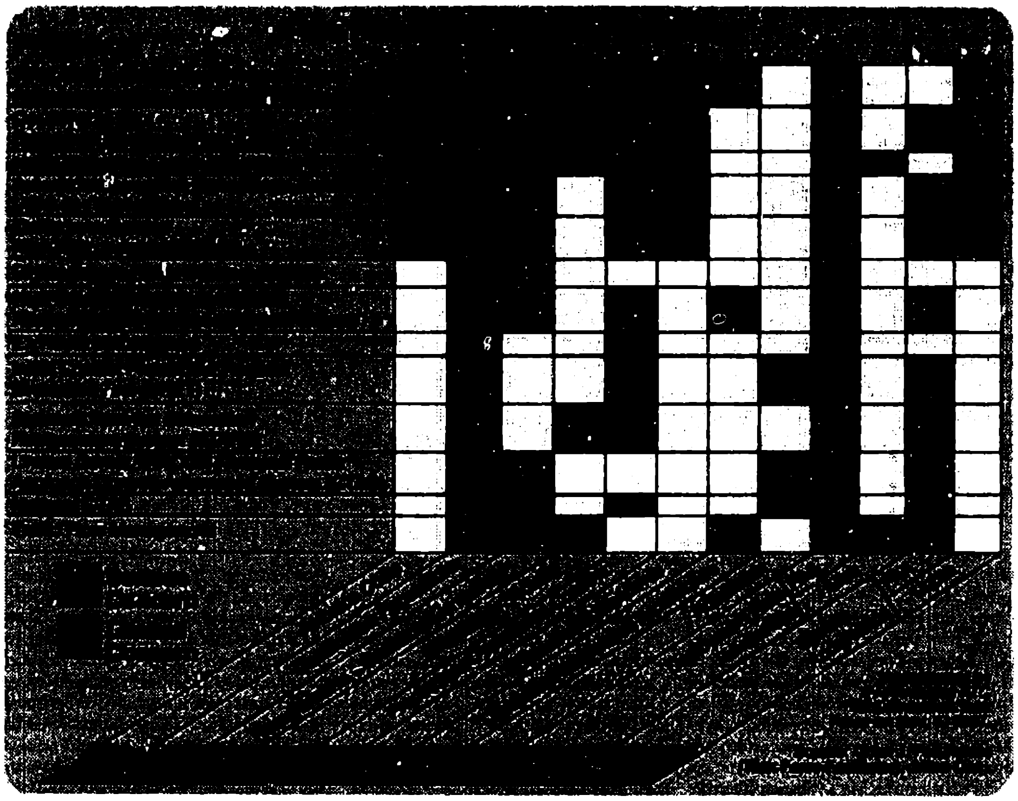
(3) **New Air Traffic Control technology**, including satellite guidance and communication, computer systems, interfacing with foreign civil aviation authorities, and, in general, ATC equipment modernization.

(4) **New operational concepts** such as free flight.

(5) **Funding of competing** transportation technologies such as high-speed train or magnetic levitation (MAGLEV).

Countless technical papers and demonstration projects have been published on all of these ideas. Most actors of the Air Traffic Control system believe that *"technology is the key to improving capacity"*[41]. Yet, a visitor to the Terminal Radar Approach (TRACON) facility at Logan airport is still greeted by controllers with a complaint on the age of the computers used there.

The variety of potential solutions may actually explain why none has been implemented until now. In its decision-making process, the FAA often seems to be "[...] a centipede that runs in all directions at once"[42]. This appears clearly on table 1-10 below, taken from the assessment by the FAA/Industry ATC modernization task force.



Source: Aviation Week, February 2, 1998, p. 44.
Table 1-10: Risk factors for key FAA programs

This table shows that the task force sees most FAA modernization programs difficult to implement. It echoes a long list of General Accounting Office reports on the Federal modernization effort and its exact waste ($1.5 billion as of 1998, according to GAO [1998]). It

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[41] McLauchlan [1993].

[42] Aviation Week, February 2, 1998, p. 48.

shows how ATC innovation does not happen easily. At least two reasons can be given to explain these difficulties:

(1) **The FAA tried to modernize too many elements of its organization at the same time:** "We shot for the moon. We tried to do advanced technology, computer replacements, new procedures, new software, and new decision support services all at once. We didn't realize the full scope of human factors. [...] We underestimated the magnitude of the change." (Steve Zaidman, quoted in IEEE spectrum, August 1997).

(2) **Air Traffic Control research is not adequately funded.** "It's tough to run, build and fix a system at the same time" (Phil Boyer, quoted in Aviation Week, February 2, 1998). Only two agencies, NASA and FAA, are funding research on Air Traffic Control, and the needs of this system are so specific that it does not benefit from research in other areas. In consequence, contractors are unable to meet FAA requirements. Congress has funded investments but not the fundamental and basic research behind them[43].

On the user side, airline innovation is not driven by congestion. It is for instance difficult to convince airlines to "buy a new aircraft technology [civil tilt-rotor] to operate into a facility that is not yet built to serve an unknown level of traffic at a yet to be determined fare."[44] Under strong competitive pressure, they maintain their hubs at the largest airports in the country, privilege high-frequency regional aircraft to very large ones, etc. There is only one concept that has interested them[45] in the current major capacity initiatives planned by the FAA: the so-called "free-flight" concept, providing airspace users with freedom to choose their path and speed in real-time. Yet, nobody hopes that it can be applied as the level of terminal areas around airports, which is precisely the focus of this thesis[46].

It is similarly puzzling to notice that, while airports are clearly identified as the key air transportation bottlenecks, ICAO's "Communications, Navigation, Surveillance/Air Traffic Management" concept (CNS/ATM) does not propose substantial innovations to resolve this issue but focuses on aircraft navigation technology.

1.3.2 The current practice of airport improvement

However disappointing this may sound, in their current practice, airports and the FAA rely on traditional solutions. Every year, the Office of System Capacity (ASC) publishes new *airport capacity studies* in which it identifies, in collaboration with local airport authorities, pilots and Air Traffic Controllers, specific solutions for a large airport using simulation of operations on the airfield. These capacity investments are yearly reviewed in the *Aviation*

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[43] Congressman Norman Y. Mineta must understand that "[we are] far away [...] from receiving any tangible benefits from the technological advances we've been funding for years". (House of Representatives [1995])

[44] Quoted by Ausrotas [1991], who mentions a 1991 Boeing study forecasting 1200 civil tiltrotor aircraft by the year 2000.

[45] The concept actually originated at United Airlines.

[46] And nobody believes the FAA will apply it either, see Aviation Week, April 27, 1998, p. 59.

Capacity Enhancement (ACE) plan. The following table shows the specific solutions that are actually considered in the 1997 ACE plan.

Airfield Improvements	**No. of airports**
Construct third parallel runway	*14*
Construct fourth parallel runway	*6*
Relocate runway	*6*
Construct new taxiway	22
Runway extension	23
Taxiway extension	*18*
Angled exits/ improved exits	29
Holding pads/ improved staging areas	29
Terminal expansion	*17*
Facilities and Equipment Improvements	
Install/ upgrade Instrument Landing Systems (ILS)	*29*
Install/ upgrade Runway Visual Range (RVR) instrument	*10*
Install/ upgrade lighting system	*13*
Install/ upgrade VHF Omnidirectional Range stations (VOR)	*8*
Upgrade terminal approach radar	*1*
Install Airport Surface Detection Equipment (ASDE)	*9*
Install Precision Runway Monitor (PRM)	*12*
New air traffic control tower	*4*
Wake vortex advisory system	*10*
Operational Improvements	
Airspace restructure/ analysis	*11*
Improve IFR approach procedures	*28*
Improve departure sequencing	*7*
Reduced separations between arrivals	*24*
Intersecting operations with wet runways	*4*
Expand TRACON /Establish TCA	3
Segregate traffic	3
De-peak airline schedules	*8*
Enhance reliever and airport system	22

Note: The numbers refer to the number of airports for which the alternative has been recommended or completed, out of 39 airports studied. Quoted from FAA-ASC [1997].

Table 1-11: Actual methods used to increase capacity considered by the FAA

As quoted from an airport manager, the ACE approach amounts to no more than "tinkering": "We're not really adding the new capacity that can come only with new airports and new runways."[47] Today, no new commercial airport is planned in the United States. Of the top 100 airports, only one airport, Memphis, completed a new runway in 1997. Most alternatives recommended by airport capacity design teams take many years (if they do) to get implemented.

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[47] AVIATION WEEK, November 21, 1988.

1.3.2.1 THE CASE OF LOGAN AIRPORT

This section is based on the airport capacity study that was conducted at Logan Airport between 1987 and 1990. It both provides some background for the next chapters and an extreme case of the political and operational issues associated with airport capacity increase.

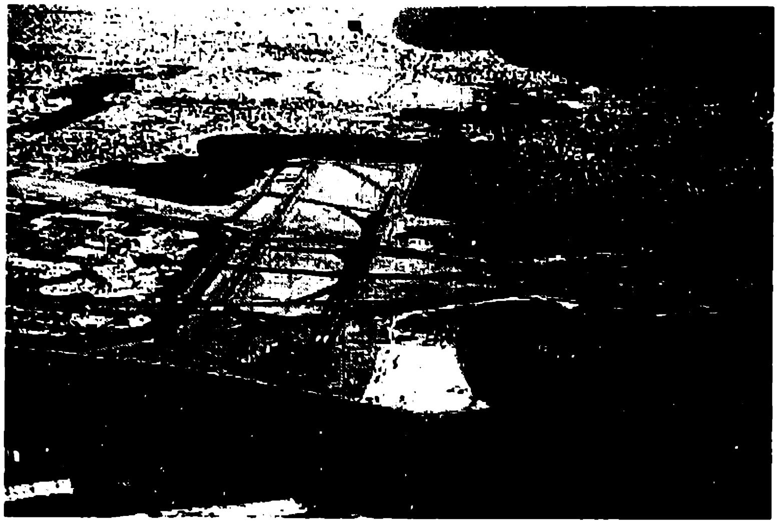

Figure 1-12: Aerial view of Logan Airport

Logan Airport enjoys a remarkable location on the edge of Boston Harbor, four miles from downtown. It is built on landfills and is surrounded by water and the residential areas of East Boston and Winthrop. These communities are sensitive to airport noise and have obtained a court order that prevents Logan from expanding beyond its existing property and low water marks.

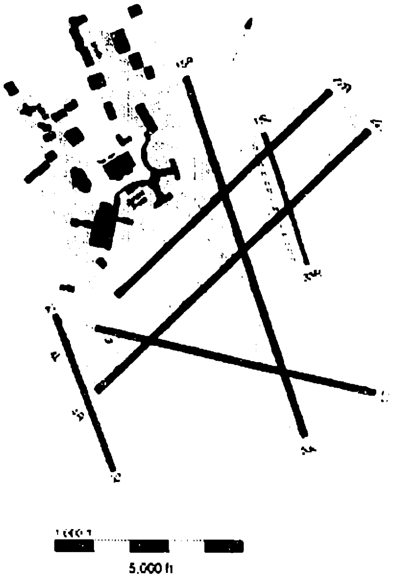

Figure 1-13: Current layout of Logan Airport, including the projected runway 14/32

The current layout of the airport includes 5 runways conventionally named by their headings (rounded to the closest tens degrees) in both directions: 4 Right/22 Left, 4 Left/22 Right, 15 Right/33 Left, 15 Left/33 Right and 9/27.

The methodology followed in airport capacity studies can be decomposed in four steps:

(1) Identification of potential strategies to enhance the capacity of the airport, as varied as possible.

(2) Precise definition of the impact of each of these strategies on operations at the airport, under each of the possible configurations.

(3) Estimate of these impacts on a simulation model of operations.

(4) Recommendation of the interesting strategies, based on their potential impact and their feasibility.

In the case of Logan Airport, the design team examined the following list of 27 improvements:

Strategy A: Separation of Small And Jet Aircraft Operations

A-1 New commuter Runway 14/32, unidirectional

A-2 New commuter Runway 14/32, bi-directional

A-3 Extend Runway 15L/33R to 3,500' with new taxiway

A-3a Combine alternatives A1 and A3

A-3b Combine alternatives A2 and A3

A/B-4 Removal of noise restrictions on arrivals on Runway 22R

A-5 400 feet westward extension of Runway 9 for commuters to hold short of Runway 15R during daylight VFR dry conditions

A-6/D-2 Application of Microwave Landing Systems (MLS) technology with new procedures (mainly for high-angle commuter approaches to avoid wake turbulence)

A-7 Simultaneous parallel approaches to Runway 33L, circle to Runway 4L in marginal IFR and calm winds

Strategy B: Expand The Number of Runways For Simultaneous Jet Operations

B-1 200 feet east extension of Runway 27, to allow landings hold short on Runway 22L, in daylight VFR dry conditions

B-2 Simultaneous approaches to Runways 4R, 4L, 22R & 22L in less than VFR 1 conditions

B-3 Simultaneous IFR approaches to Runways 27, 22L, 4L & 33L under IFR

A/B-4 Removal of noise restrictions on Runway 4L departures

A/B-4a Remove noise restrictions on Runway 4L and extension to a new Taxiway B

B-5 Side step approaches from Runway 4R to Runway 4L

B-6 Utilize fan headings for aircraft departing Runways 22L and 22R

B-7 Use of hold-short procedures under VFR wet conditions for turbojet aircraft on runways 15R (short of 9), 22L (27), and 33L (4L)

Strategy C: Improve Taxiway Circulation

C-1 New parallel taxiway between Runways 4L/22R and 4R/22L

C-2 New south exit parallel taxiway for Runway 27

C-3 Add fillets at intersection of Taxiways D and C with Runway 15R/33L

C-4 Staging areas for runways 15R/33L, 27, 4R, 22R and at the intersection of 33Land taxiway G

C-5 New taxiway from the end of Runway 27 to the end of Runway 33L

C-6 Extend Taxiway D to Runway 4R/22L

Strategy D: Lowering Approach Minimums
D-1 Install CAT II/II ILS on runways 15R, 22L, 27, and 33L
A-6/D-2 Utilization of Microwave Landing Systems (MLS) technology
D-3 Reduce minimums to 250 feet and ¾ mile on Runway 22L for CAT I approaches
Strategy E: Demand Management Policies
E-1 Increase the percentage of large and heavy jets in the fleet mix
E-2 Redistribute airline schedules within the hour
Strategy F: Develop More Efficient Use of The Airspace
F-1 Improve metering, spacing and segregation of heavy jets
F-2 Benefit of Wake Vortex Advisory System (VAS)
F-2a Benefit of Wake Vortex Avoidance System (WVAS)

Table 1-12: Improvements examined by the Logan Capacity Team, FAA-ASC [1992]

For improvements to have a significant impact, they must be used under conditions that are either frequent or seriously reducing capacity. Depending on weather conditions, the tower supervisor selects a runway configuration that can accommodate certain mixes of arrivals and departures. Logan airport often operates under the following four main configurations:

(1) Arrivals on 4L and 4R, departures on 4L, 4R and 9.

(2) Arrivals on 27 and 22L, departures on 22R and 22L.

(3) Arrivals on 33L and 33R, departures on 27 and 33L.

(4) Arrivals on 9, 15R and 15L, departures on 15R and 9.

Because of the complex layout of the airport, these configurations require a precise coordination of operations. This coordination is particularly difficult under poor weather conditions, so that it often becomes necessary to limit arrivals to certain runways, for instance 4R in the first configuration. These concepts will be further defined in chapter 2.

In general, the airport capacity design team has focused on operations that could be handled with limited modifications of the layout and investments in equipment. There is room for a new runway in only one area of the airport property. Runway extensions were also considered whenever they would allow independent operations or hold-short procedures. For instance, the motivation for strategy A arises from the large percentage of regional aircraft that operates at Logan airport. These aircraft are slower and require large separations with large aircraft. Thus, organizing independent operations for small aircraft and jets under various configurations and weather conditions should have a positive impact:

(1) Construct/extend runways under configuration 3.

(2) Allow jets to use runway 4L under configuration 1.

(3) Extend runway 9 to permit commuter aircraft to hold short of runway 15R under configuration 4.

(4) Design a new efficient configuration using runways 33L and 4L.

Strategy B aims at the development of similar procedures that would allow for hold-short or simultaneous operations.

Modifications to the taxiway system (strategy C) can have three positive impacts:

- Reduce ground congestion and relieve ground controllers.
- Increase departure-sequencing flexibility to take advantage of divergent departure routes.
- Reduce runway occupancy time by providing better-located exits.

The fifth group of strategies (strategy E), because it was voluntarily designed to have a moderate impact, is rejected by the capacity team on the grounds that "[it results in] moderate benefits and [because of] the stated policy of ATA opposing such an initiative".

In conclusion, the current practice of airport improvement remains conventional, even at the most constrained airports such as Logan, and requires large investments in new equipment. Solutions are never straightforward but rather come from an in-depth understanding of the bottlenecks that affect the airport. Many innovative concepts have been proposed and demonstrated, yet all actors of the NAS have remained very conservative. There are many reasons why solutions to the airport congestion problem are still searched within narrow boundaries, the most obvious being:

- **The price and frequency competition between airlines**: congestion is a smaller evil than bankruptcy, and
- **The unique position of the FAA** supposed to invent new Air Traffic Control concepts with $150 M R&D funding[48].

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[48] OTA [1994] rightfully points out that a large portion of the Facilities and Equipment funds are used for R&D, which makes a total of $672 M (plus $50 M within NASA) federal ATC R&D in 1994. These funds are however aimed much more at new technologies than at fundamental research.

CHAPTER 2

THE CHALLENGING TASK OF DESIGNING INNOVATIVE TOOLS TO IMPROVE AIRPORT OPERATIONS

The previous chapter has shown that the solutions currently used to alleviate congestion in the NAS are drawn from a small group of operational and airfield modifications. The controllers' work environment has been surprisingly stable despite the "highly technological" content of their job. As described in section 1.3.2, the current practice privileges conventional improvements despite the fact that they are neither very cost-effective nor politically easy to achieve[1].

At the same time, new tools and new modes of operation have proven difficult to design and implement. Beyond policy and economic reasons, various factors explain this situation:

- *The pervasive issue of integration:* a highly procedural organization does not accommodate easily new systems since those must precisely fit its practices.
- *It is always challenging to evaluate the reaction of other actors.* The performance of the system is a combination of the behavior of all pilots and all controllers. Each airline and each control facility adapts to whomever it interacts with. Local optima are rarely global. Ripple effects are frequent in the Air Traffic Control system.
- *The final improvements are often elusive.* What about workload? Flexibility? Delays? Complexity? Many projects have aimed at quantifying the impact of new technologies on the ATC[2]. For instance, Boeing has organized a "CNS/ATM Focused Team" to determine in which direction manufacturers and airlines want the new CNS/ATM infrastructure to evolve[3]. Specifically, this complexity does not facilitate

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[1] Many improvements in Logan Airport capacity enhancement plan were not further examined because of policy considerations.

[2] See for instance LEE, KOSTIUK *et al.* [1997].

[3] According to this team (BOEING [1997]), estimating the dollar benefits of a new infrastructure requires to evaluate the impact in terms of: (1) cost/fee savings, (2) block time reduction and increased utilization, (3) schedule recovery, (4) reduced fuel use, (5) reduced fuel reserves, increased range, increased payload, (6) lower

FAA's application of the 1993 Government Performance and Results Act (GPRA) that requires to balance the costs and benefits of its investments and to identify *quantifiable performance goals*.[4]

This chapter delves into these issues by articulating them around the following three questions:

(1) What is the current work environment of a large airport control tower?

(2) How information has been integrated in the system?

(3) What has happened with the successful (and less successful) innovations that have been introduced in the Air Traffic Control system in the last decade?

2.1 THE CURRENT WORK ENVIRONMENT AS A BASELINE

To select airport improvements, it is necessary to have estimates of their impact on airport operations under the various configurations that are being used. In general, the tower supervisor selects the configuration that provides the highest capacity given the current weather conditions and operational constraints. This process is based on the following equation (in which improvement is synonym to delay reduction).

$$\mathit{Total\ improv't} = \sum_{all\ cfg} \%\ \mathit{ops\ under\ cfg\ i} \times \mathit{delay\ reduction\ per\ op.\ under\ cfg\ i}$$

This approach is for instance used by LEE, KOSTIUK *et al.* [1997] to estimate the effects of NASA's Terminal Area Productivity (TAP) program that aims at reducing the impact of bad weather on airport capacity. It can go one step further when it looks at how to minimize *costs* by transferring delays from one element to another.

Designing new tools that have a significant positive impact on the system requires a clear understanding of airport operations dynamics in order to focus on *bottlenecks*. Based on past studies and observations at Logan Airport, it is reasonable to identify three potential bottlenecks in airport operations: (1) the runway system, (2) the taxiway system and (3) controllers' workload. They are described in the next sections.

2.1.1 Runway system capacity

2.1.1.1 PHYSICAL LIMITATIONS ON RUNWAY SYSTEM CAPACITY

The terminal area that surrounds a large airport aggregate important departure and arrival flows. While these flows can be relatively easily segregated in the airspace, they must

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diversion, delay and cancellation costs, (7) increased passenger satisfaction and (8) ability to provide more flights.

[4] Metrics are currently under development, see BOLCZAK, BROWN *et al.* [1997].

be strictly coordinated when aircraft use the runway system. This coordination is motivated on two grounds:

(1) To prevent collisions at all times.

(2) To limit the effects of wake vortex[5] caused by large aircraft on following aircraft.

It is achieved using two fundamental principles. First, there can be only one aircraft at a time on a runway since an aircraft can always be forced to stop on it and the following traffic must be diverted. Second, terminal area separation standards are defined. These standards[6] provide for the necessary separation to limit the effects of wake vortex and to prevent collisions. For instance, separation requirements on final approach between successive arrivals on the same runway are given for Logan Airport on table 2-1.

Leading aircraft type	Heavy trailing	757 trailing	Large/Medium trailing	Small trailing
Heavy	4	5	5	6
757	4	4	4	5
Large/Medium	2.5	2.5	2.5	4
Small	2.5	2.5	2.5	2.5

Table 2-1: Separation requirements on final approach between arrivals on the same runway (nm)

In the Terminal Radar Approach Control facility (TRACON), the ATC facility dedicated to the control of aircraft in the airspace surrounding a large airport, a controller continually monitors landing aircraft to make sure that they maintain these separations.

The separation constraint differs a little on the departure side. It is necessary to deal with separation requirements before takeoff because they are stricter at a distance from airports. This occurs for instance when two aircraft plan to take the same Standard Instrument Departure route (SID) one after the other. There are three methods that enable controllers to deal with this situation:

(1) *Delay the trailing aircraft* so that the two aircraft be sufficiently separated as soon as they are airborne. This method is used when there is not much traffic.

(2) *Vector the trailing aircraft in the air,* so that it slows down in comparison with the leading aircraft. A TRACON controller must guide these operations, and they imply a longer flight time for the trailing aircraft. This is shown on figure 2-1 below.

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[5] Wake vortex are mainly generated by landing aircraft and may affect other aircraft landing and taking off nearby.

[6] A detailed account of their historical development and current definition can be found in THOMSON [1997].

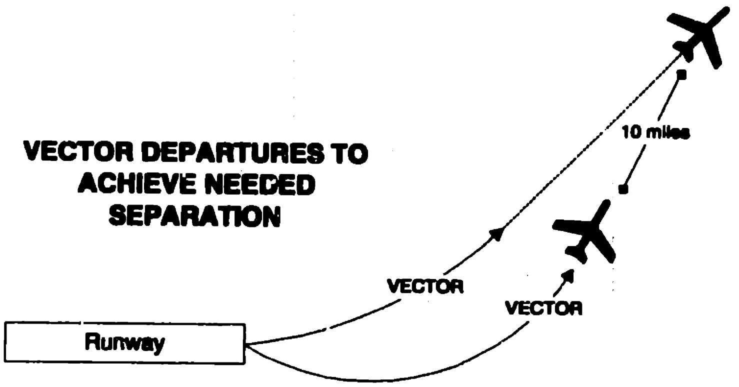


Figure 2-1: Vectoring aircraft to achieve airborne separations after takeoff

(3) *Sequence departures between SIDs*: by alternating departures using different routes, it is possible to apply the low runway separation standards and meet the higher airborne separation standards. This is described on figure 2-2 below.

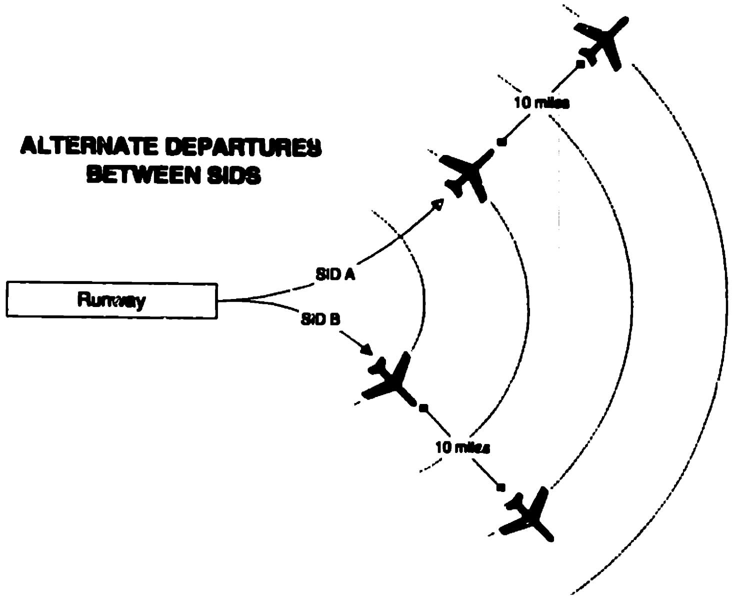
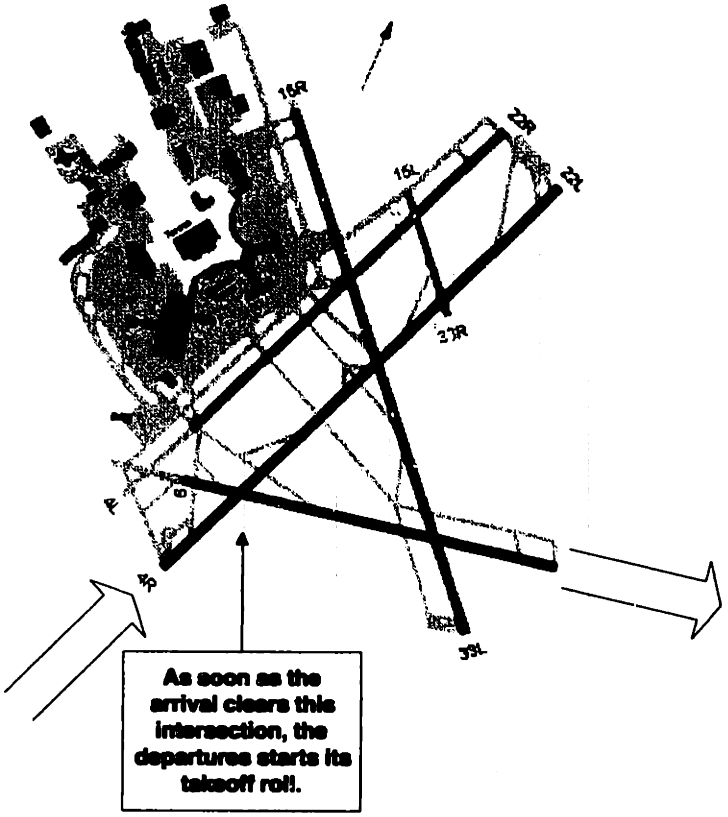


Figure 2-2: Alternating SIDs to achieve airborne separations after takeoff

Similarly, separations apply to operations occurring on different runways, except when the distance between them is sufficient to ensure that problems (missed approach, position error, aircraft immobilized on a runway) occurring on one will not affect operations on the other. For instance, at Logan Airport, departures on runway 9 are released as soon as arrivals on runway 4R have crossed the intersection, as described on figure 2-3 that follows.



As soon as the arrival clears this intersection, the departures starts its takeoff roll.

Figure 2-3: Coordination of arrivals and takeoffs between runway 4R and 9 at Logan Airport

2.1.1.2 THE TRADE-OFF BETWEEN DEPARTURES AND ARRIVALS

The sum of these separation constraints builds up into what has been identified as a convex, non-linear functional relationship (NEWELL [1979], GILBO [1993]). Any point (x arrivals, y departures) under the capacity curve shown on figure 2-4 can be achieved given the weather conditions and aircraft mix.

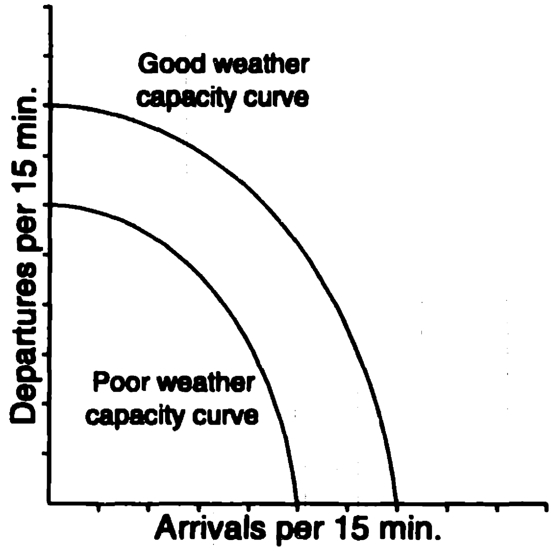


Figure 2-4: Typical runway system capacity curves

This representation is more realistic than traditional capacity figures that are usually estimated for a 50% arrival/departures mix, as shown on table 2-2 below for Logan Airport. Besides, it shows the actual tradeoff between departures and arrivals. Although it is true that, in the long term, the aircraft mix is 50% arrivals/departures, observations at Logan control tower have shown that supervisors pay constant attention to the forecasted mix of arrivals and departures, for instance to select the specific configuration that will be able to handle more efficiently a large departure flow expected in two hours.

Config.	Weather	Arrivals		Departures			Total	
	conditions	4L	4R	4L	4R	9	Saturation	Operational
401DV	VAPS	29	39	23	8	36	135	122
404DV	VAPS	26	27	28	26	0	107	96
405DI	CATI	0	24	12	12	0	48	43

Source: Flight Transportation Associates. 1993 Fleet mix, 50% arrivals.

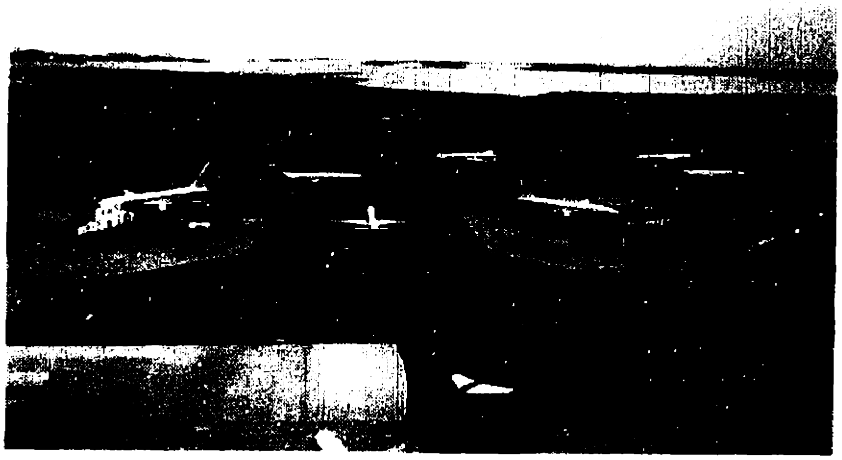
Table 2-2: Examples of FLAPS simulation software capacity estimates

Considering the complex choice of the optimal configuration to handle future traffic, it seems appropriate to provide supervisors with help, at least through the best possible forecasts of future demand.

2.1.2 Taxiway system constraints

The taxiway system is located at the interface between the two essential elements of an airport, the gates (controlled by airlines) and the runways (controlled by the FAA). This is why it is often seen as a plain buffer to accommodate overflow of both systems: the departure queues for runways, and staging pads and parking areas for gates. It can however become congested to the point of impacting airport operations when not enough taxiways serve a given runway or terminal. Then, overtaking an aircraft that incurs some delay is a complex operation. Many urban airports, especially in Europe, have to deal with this constraint, which can be characterized by either:

(1) Impacting operations in the vicinity of a terminal, typically preventing access to a gate because of operations at others.



Note: Only one movement is allowed at any time in this area of Logan airport located between terminal B and C.

Figure 2-5: A United Airlines jet waits in the so-called horseshoe before accessing the taxiway system

(2) Forcing controllers to build their departure sequence earlier because aircraft must be funneled through a single taxiway to the runway end. Then, controllers have difficulties to accommodate delayed aircraft in the single line. Or,

(3) Affecting runway operations, when arrivals can only exit on a limited number of taxiways, and accumulate on this taxiway for any reason.

2.1.3 Controller's workload

Controller's workload is a major concern in the design of the Air Traffic Control organization. There are limits to the number of aircraft a controller can handle, and these limits must not be exceeded. To answer this issue, procedures have been precisely defined for each position of every control facility. Each controller has a detailed list of tasks to perform, and is solely responsible for them. These tasks are described in official documents such as FAA order 7110.65H that defines *terminal airport traffic control* procedures or order BOS TWR 7110.11D that contains *Boston Air Traffic Control Tower standard operating procedures.*

2.1.3.1 TOOLS TO LIMIT WORKLOAD

Various schemes are implemented to limit controller's workload. For example, since delaying an aircraft in the air is a time-consuming duty, information on expected delays in the vicinity of an airport (induced by high demand and/or low capacity on the arrival side of this airport) is sent to airspace controllers in surrounding control facilities. Then, these controllers can slow down the aircraft under their control bound for the congested destination, which in turn reduces the first controllers' workload. In many cases, Ground Delay Programs are implemented to delay flights bound for a congested airport *before takeoff*.

Inside a control tower, workload is limited through two means. Pilots initially contact a controller, named Clearance Delivery (CD), to confirm that they are ready to leave. If necessary, this controller's workload is limited by the frequency congestion that occurs when too many pilots try to contact him/her. At Boston tower, all other controllers *take the initiative* to contact pilots when they have decided where each aircraft must go. This allows them to precisely decide of their workload.

2.1.3.2 BOSTON TOWER ORGANIZATION

The organization of the control tower at Logan Airport was studied in detail in the framework of this research. Its main features are reviewed here.

1. GENERAL ORGANIZATION

Traditional staffing at Boston tower includes 6 controllers, 5 of which in communication with pilots, a supervisor and a traffic management coordinator. In addition, a controller takes care of helicopters when needed.

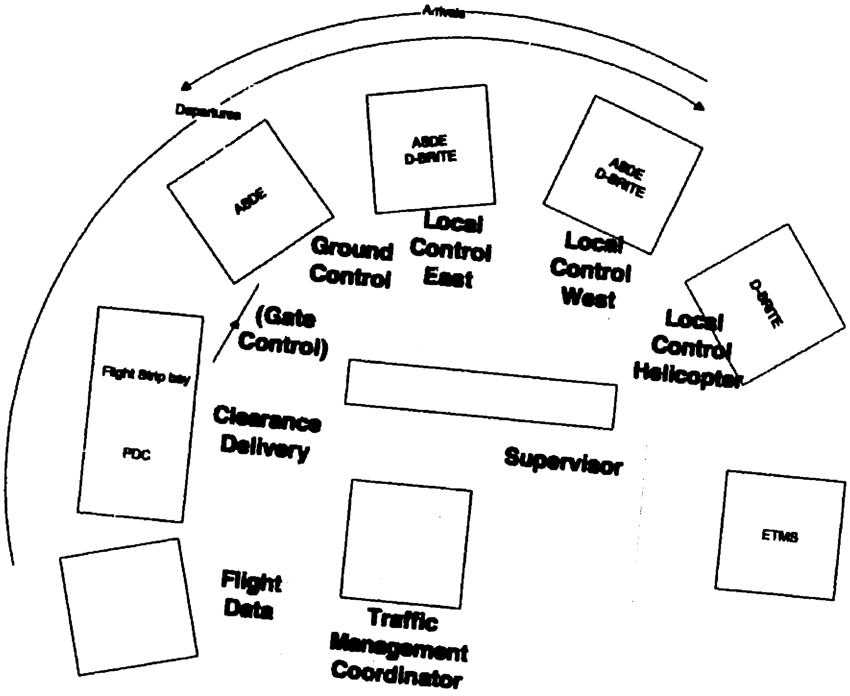


Figure 2-6: Layout of Boston Air Traffic Control Tower

A departing flight usually goes through the following positions:

(1) **Flight Data**, managing data that arrive at the tower (mainly flight strips and weather).

(2) **Clearance Delivery** (CD), who receives the first calls from pilots. Most jets receive electronically their clearance 30 minutes prior to departure through the Pre-Departure Clearance (PDC) system. Other flights have to request first a clearance from this controller. He/she takes the initiative to hold flights if Ground Control (GC) is congested. He/she can for instance take care of the towing operations around terminal E. Pilots call "ready to push" and if GC is/looks OK (most cases), CD releases them with the sentence "monitor Ground Control on 121.9 for pushback". The flight strips bay looks like this:

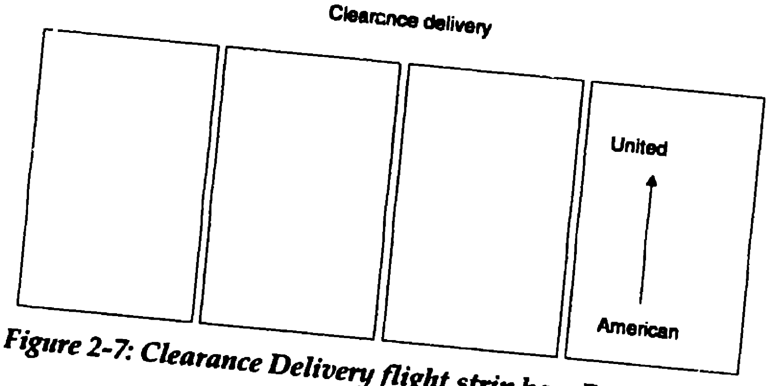


Figure 2-7: Clearance Delivery flight strip bay, Boston tower

(3) Official procedures include a **Gate Control** (GC) position. However, since most clearances are given automatically, CD can handle GC tasks in case of rush without need to fill this position. It is not clear whether it is actually filled at some time.

(4) **Ground Control** (GC) manages all movements on taxiways that do not have access to active runways. This controller takes the initiative, upon reception of the flight strip (sent along the rail represented as an arrow on figure 2-6), to contact each aircraft. While doing so, he/she examines the path this aircraft should take to reach its departure runway, and describes it to the pilot.

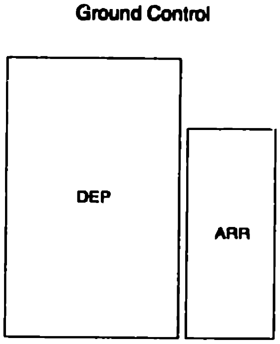


Figure 2-8: Ground Control position flight strip bay, Boston tower

(5) **Local Control East** (LCE) uses both a surface surveillance radar display (ASDE-3) and near terminal airspace traffic information (ASR-9 on D-BRITE). A video camera located above the flight strip bays allows TRACON controllers to see which aircraft are airborne.

(6) **Local Control West** (LCW) is equipped similarly.

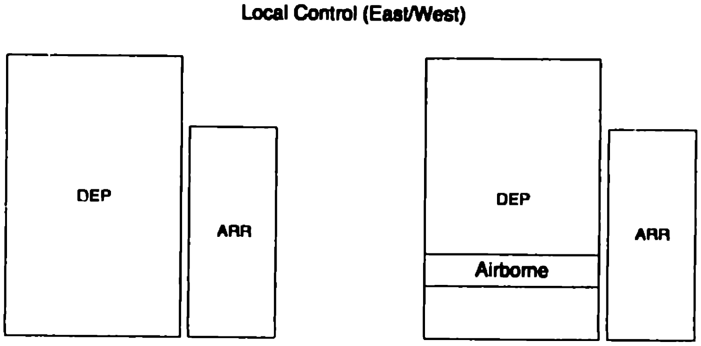


Figure 2-9: Local Control flight strip bay, Boston tower.

2. TRAFFIC MANAGEMENT

Traffic management is now handled by a dedicated controller, the Traffic Management Coordinator (TMC). His/her tasks include the implementation of flow restrictions taken by other facilities and decisions concerning Logan Airport flows. This controller shares with the TRACON Traffic Management Unit a log of all these restrictions.

Restrictions are of four types[7]:

(1) *National and Local Ground Delay Programs*, that apply to specific aircraft bound for congested airports. New clearance times (EDCTs) are sent to the tower and transmitted to pilots and each airline operating center.

(2) *Severe Weather Avoidance Programs* (SWAP) rerouting flights around major bad weather concentrations.

(3) *Departure Spacing Programs* are traffic management decisions taken by en-route centers (ARTCC). An advisory such as "ORD MIT .... Provide ZOB 20 MIT .... 1115-1300Z due volume ..... DSP in effect" is printed in all Boston Center towers. It asks for 20 miles in trail (MIT) between departures bound for Chicago O'Hare (ORD). This is because Chicago En-route Center (ZOB) probably asks Boston Center for 10 MIT at the boundary between the two centers. Thus, Boston Center asks 20 MIT to all airports under its supervision.

(4) *Ground stops* are the most constraining decisions: because of major unexpected reduction of capacity, an airport asks that no aircraft bound for it be released.

Decisions regarding Logan Airport are of two types:

(1) *The choice of configuration* is made by the supervisor in agreement with the TMC. It is based on the consideration of weather parameters (the most important being ceiling, visibility, and wind), forecasted demand (taken mainly from a display of *scheduled* demand, and sometimes from the ASD[8]) and environmental constraints (whenever possible, the tower must vary the flow patterns to reduce noise).

(2) *The type of restrictions that applies at the airport.* Mirroring the restrictions described in the previous paragraph, the airport may operate under free flow (i.e. no restrictions), metering (arrivals are slowed down in the TRACON and/or center to achieve an Acceptance Rate given by the tower), EDCT (when a GDP is implemented at Logan) or Ground Stop (when conditions impose the blocking of all aircraft bound for Logan). These decisions are often straightforward because they are due to the fact that the airport operates under a low capacity configuration.

Once a traffic management decision is deemed necessary, it is important to select the most appropriate moment to implement the changes since operations can be strongly affected by the transition.

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[7] This classification is based on conversations with controllers and BOOTH [1994].

[8] The ASD shows real-time data on airborne aircraft bound for any airport. See section 2.2.1.1 for more details.

2.1.3.3 FORECASTING WORKLOAD

Since airborne aircraft have a major impact on controllers' workload, and since these aircraft may not be able to land because of runway system capacity limitations, the FAA tries to forecast as well as possible the future workload of every facility. Forecasting demand is however a highly challenging task. While airborne aircraft are likely to follow their flight plans unless affected by weather or airspace congestion, the actual *departure* demand is more elusive.

The reason for it can again be found in the dual management of the National Airspace by both the FAA and airlines. Airlines serve their customers by providing scheduled flights at their preferred times. They offer these services through published schedules that are mainly used by travel agents. The most widely used of these schedules is the Official Airline Guide, which shows, a couple months in advance, what each airline *plans to fly* on any given day. However, since travel agents work on networked computers, these schedules evolve within the Computer Reservation Systems until a few days prior to actual flight. Worse, the actual decision to provide a flight at a given hour is often taken on the day of operation. Major carriers cancel an average 3 to 4% of their operations *every day* and these cancellations are not necessarily related to technical problems with some aircraft. Differences between schedules and actual operations are variable. Major airlines usually follow their schedules with more precision than regional carriers since it is obviously easier to reschedule 10 passengers on the next flight than 120. Nevertheless, competitive scheduling and reactions are frequent even between large airlines.

Not only airlines play this scheduling game in order to maximize their revenues and aircraft utilization, they also do not necessarily depart at the scheduled hour. This occurs mainly for two reasons. First, the gate operations that are performed on an aircraft are complex and are not always finished as expected, especially since airlines reduce turn-around times and staffing to increase aircraft utilization and productivity[9]. Second, flights are sometimes delayed to allow late connecting passengers on board.

In consequence, two operational tools are used to forecast workload. The main tool is a count of the flight plans filed to depart and arrive at a given airport in each of the next hours. For the reasons exposed above, this forecast is often poor. The Aircraft Situation Display[10] is used to obtain more precise forecasts of arrival demand, but only punctually.

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[9] See GITTELL [1995].

[10] This system is presented in section 2.2.1.1.

2.2 AN OVERVIEW OF THE DATA AVAILABLE ON AIRPORT OPERATIONS

In this section, the various sources of data available on airport operations are reviewed. Data are vital to intelligent operations. The example of the workload forecasts showed that the lack of good quality data was a serious concern.

Data come from one of the three following sources:

- The Federal Aviation Administration facilities
- Airlines
- The regional weather centers

The three first sections simply describe these data sources in order to determine which are the ones suitable for research on airport operations. The argument is made in the fourth section that, because these sources are quite limited, the current situation impedes the full development of information systems to support tools that minimize the impact of congestion.

2.2.1 FAA data

2.2.1.1 THE ENHANCED TRAFFIC MANAGEMENT SYSTEM

Compared with other large-scale technical systems, FAA's Air Traffic Control facilities make up a remarkable information system that continually tracks flights as soon as their flight plans are filed. Yet, following the workload concerns identified in section 2.1.3, each controller only has access to the situation of the aircraft under his/her responsibility. The Enhanced Traffic Management System has thus been designed to achieve two functions: (1) to display current aircraft positions and (2) to automatically generate alerts when projected demand exceeds alert thresholds.

The first function provides snapshots of all IFR flights in the entire NAS. It appears on the Aircraft Situation Display (ASD), now installed in every large ATC facility and at the major airlines operating centers, which can instantly display all the aircraft bound for a given airport, thus providing a forecasting tool for arrivals based on actual airborne traffic. This formidable picture comes through a huge data reduction process: all messages (called "Z" messages) generated by host computers of every ATC facility are sent to the National Transportation Systems Center (Volpe center) that continuously updates the display.

Using this data to design decision support systems for airport operations poses three problems:

(1) *The amount of data generated is huge* since many messages are sent during each flight.

(2) *These data are imprecise with respect to the exact time of operations.* Departure messages (DZ) are recorded when a host computer recognizes that a flight has taken off, but arrival messages (AZ) can "time-out" more than 20 minutes before the actual landing. Besides, when the host computers are particularly busy, they stop sending these Z messages and the data are not recorded.

(3) *These data do not cover ground operations:* there are surface radars (ASDE) in U.S. control towers, but they are neither very precise nor linked with the flight database of the host computers. From the point of view of the Air Traffic Control system, flights are just plain paper Flight Progress Strips (FPS) during their ground movements. Since ETMS can not record these operations, it generates take-off time forecasts based on historical 3-week performance (difference between DZ messages and gate departures filed in the flight plans). For each airline-airport combination, the median total ground time is used if statistically significant, otherwise a default value of 10 minutes is applied[11]. In the absence of gate information, airline affiliation appears as the best distinguishing factor.

In conclusion, ETMS data are not suitable for research on airport operations. They are however useful to study the arrival flows into airports.

2.2.1.2 PREFERENTIAL RUNWAY ASSIGNMENT SYSTEM DATA

As described in section 2.1.3.2, all operational flight data are written down by controllers on the Flight Progress Strips. These strips are archived for a duration of 15 days before being discarded. There is no digital version available.

Similarly, Control tower supervisors record in logbooks the configurations under which they operate each airport, but this data is usually not accessible in digital format either. Since 1993 however, in the case of Logan Airport, the Massachusetts Port Authority has implemented a Preferential Runway Assignment System (PRAS). Its aim is to monitor which runways have historically been used to ensure that surrounding communities are not extensively disturbed by aircraft noise.

To control this issue, a digital log of airport configurations has been instituted to have an exact measure of runway usage at all time. Logan tower supervisors log in the PRAS computer each configuration change. Additionally, these data are validated and corrected by the Massport Noise Abatement Unit using TRACON radar data.

PRAS data are public, and have been obtained for the last 4 years from the Noise Abatement Unit. The current database contains the following variables:

---

[11] See Appendix B of the ETMS functional description, VOLPE [1995].

Variable	Example	Comments
Start date	2-Jan-97	
Start time	19:20	Is also the end time for the previous record
Arrival runways	33L - 33R	
Departure runways	27 - 33L	

Table 2-3: Content of the PRAS database

Arrival and departure runways are combined to form 29 configurations, including specific details like "33L-27 CRDA[12]". Basic statistics for the period 1995-1997 show that the airport goes on average through 6 configuration changes per day (standard deviation is 2.6). This number has beer increasing in the past, with the introduction of new procedures (such as Accelerated Departure Program on 27), and, in general, more frequent changes (average change has increased from 4.8 to 6.8 between 1995 and 1997).

When analyzing these data, it is important to make the difference between time usage and operations. Because of noise abatement, configuration 14 (under which aircraft land and takeoff from the water) is used as often as possible during night operations, as appears on table 2-4 below. It is rarely used during daytime.

Cfg	All time	5:00 to 21:00	Arrival	Departure
9	23%	29%	27 -22L	22R - 22L
2	15%	20%	4R - 4L	9 - 4R - 4L
16	14%	16%	33L - 33R	27 - 33L
20	10%	11%	4R - 4L	9 - 4R
14	9%	3%	33L	15R
7	5%	4%	22L - 22R	22R - 22L
6	4%	2%	22L - 22R	15R - 22L
15	3%	1%	33L - 33R	22R - 22L
23	3%	4%	4R - 15R VA 4L	9 - 4R - 4L
17	3%	2%	33L - 33R	33L
3	3%	2%	4R - 4L	15R
1	2%	3%	4R - 4L	4R - 4L
12	1%	0%	33L - 33R	4R
4	1%	1%	15R	15R - 9

Source: PRAS data, Massport.

Table 2-4: Configuration time usage, Logan Airport, 1995-1997

51% of the configuration changes occur during the periods of low traffic between 21:00 and 6:59 a.m. During active periods, configuration changes are spread evenly with a slight preference for the period between 9:00 and 9:59 (after the morning peak), and 18:00 to 19:59 (to adapt to the evolution of demand, the airport is put into configurations such as 27 ADP/ 22L – 22R and 27 – 22L / 22R – 22L[13], away from low capacity configurations like 33L – 33R / 27 – 33L or from north bound configurations like 4R – L/9). Configuration changes per hour are shown below.

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[12] Converging Runway Display Aid, a display designed to facilitate dependent convergent instrument approach.

[13] During this hour, 60% of the changes are made to start using these configurations.

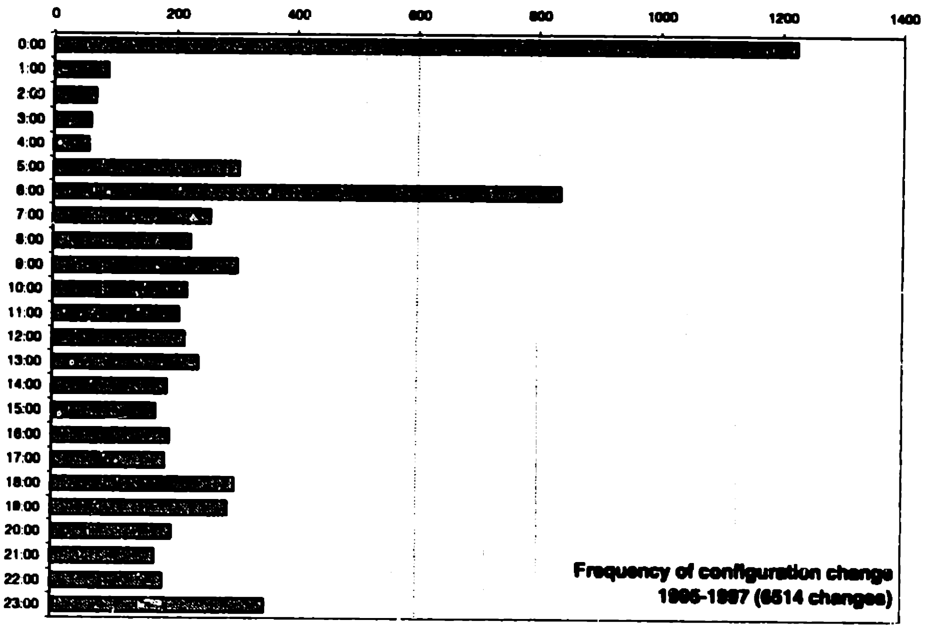

Figure 2-10: Frequency of configuration changes per hour, Logan Airport, 1995-1997

2.2.1.3 CONSOLIDATED OPERATIONS AND DELAY ANALYSIS SYSTEM (CODAS)

CODAS is a recent initiative of the FAA office of aviation policy and plans (APO) aimed at "provid[ing] a comprehensive measure of the performance of the Air Traffic Control system[14]". This system, currently under development and validation, will eventually integrate data from:

(1) FAA's Enhanced Traffic Management System (ETMS).

(2) DOT's Airline Service Quality Performance (ASQP) system.

(3) Reports from the Air Transport Association on specific gate-hold delays.

(4) APO's estimates of unimpeded taxi times.

(5) Weather reports at departure and arrival airports.

(6) Runway configuration (in the future).

Because of the two-month delay in receiving ASQP data, this system is not designed to be used for weekly planning, but for longer term planning. These databases will be integrated to estimate four delays:

(1) **Airborne delays**, the difference between actual (ASQP) flight time and planned flight time (from flight plan in ETMS).

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[14] See FAA-APO [1997]

(2) **Total gate delays**, either caused by GDP (and filed as EDCT in the ETMS), or by the airline (difference between actual departure found in the ASQP and the filed departure time in the ETMS).

(3) **Taxi-out delay**, the difference between the actual taxi-out time from the ASQP and the unimpeded nominal taxi-out time (estimated for each set {airport, carrier, season}).

(4) **Taxi-in delay**, similar to taxi-out delays.

While this project is an excellent initiative to improve data accessibility on NAS operations, it does not include new data collection systems. Besides, its progress has been slower than expected. After 3 years in development, it has not been possible to obtain these data in the framework of this research.

2.2.2 Airline data

2.2.2.1 AIRLINE SERVICE QUALITY PERFORMANCE DATA

The Airline Service Quality Performance (ASQP) data are collected by the Department of Transportation in order to calculate on-time performance statistics for the 10 main domestic airlines.[15] It includes the following ten airlines: Alaska, American, America West, Continental, Delta, Northwest, Southwest, TWA, United, and U.S. Airways. For every flight recorded, the database contains the information described on table 2-5.

This database is made monthly available to the public with a 2 month delay. The monthly files weighs between 50 and 60 MB, for about 400,000 flights. 4% of these flights originate or terminate at Logan Airport. For all airlines except Southwest, the "actual" data are automatically reported through the ACARS data link system. For instance, the gate departure time is measured by the time when the aircraft brakes are released. Since this signal used to trigger pilots' flight times, pilots were tempted to release them prior to their actual departure. This discrepancy has normally disappeared with new ways for pilots to signal the beginning of a flight. We have however performed a validation of these data at Logan Airport (see appendix 4.4 p. 132).

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[15] This "program [was designed] to ensure that airline passengers would have good information about the quality of airline service." (Rep. James Oberstar, quoted in HOUSE OF REPRESENTATIVES [1995]).

Variable	Example	Comments
FAA_CARR	AA	Airline
FLTNO	1	Flight Number
DEP_LOCID	JFK	Departure location
ARR_LOCID	LAX	Arrival location
YY	97	Year
MM	12	Month
DD	1	Day
DAYOFWEEK	1	Day of the week (1 is Monday)
OAG_DEP	0	Gate Departure time as listed in the OAG
CRS_DEP	900	Gate Departure time as listed in the Computer Reservation System within seven calendar days of the scheduled departure
ASQP_DEP	901	Gate Departure time as collected by the airline
OAG_ARR	0	Gate Arrival time as listed in the OAG
CRS_ARR	1208	Gate Arrival time as listed in the Computer Reservation System
ASQP_ARR	1152	Gate Arrival time as collected by the airline
OAGDEPDEL	0	ASQP_DEP - OAG_DEP
OAGARRDEL	0	ASQP_ARR - OAG_ARR
OAG_G2G	368	OAG_ARR - OAG_DEP (minutes, apparently replaced by the CRS?)
ASQP_G2G	351	ASQP_ARR - ASQP_DEP (minutes)
ACTDEPDEL	1	ASQP_DEP - CRS_DEP
ACTARRDEL	-16	ASQP_ARR - CRS_ARR
ACTCRSDIF	-17	
WHEELS_OFF	912	Wheels off time
WHEELS_ON	1139	Wheels on time
TAILNO	N339AA	Tail number
TAXI_OUT	11	WHEELS_OFF - ASQP_DEP (minutes)
TAXI_IN	13	ASQP_ARR - WHEELS_ON (minutes)
AIRBORNE	327	WHEELS_ON - WHEELS_OFF (minutes)

Table 2-5: Content of the ASQP database

The ASQP data have two major limitations for this study:

(1) They cover a limited share of operations at U.S. airports.

	1996	1997
Total Logan Airport operations	456,226	482,541
Total Logan Airport jet operations	252,214	265,539
Flights included in the ASQP database	186,439	196,516
% of total operations	*41%*	*41%*
% of total jet operations	*74%*	*74%*

Sources: Massport airport traffic summaries, ASQP database.

Table 2-6: Percentage of Logan Airport operations included in the ASQP database

(2) They are published with a significant delay. This means that, for the time being, they can only be used for analysis and not for real-time decisions. Nevertheless, since ACARS data are sent instantly to each airline's operating center, it should be possible, on the medium term, to obtain these data in real-time in the control tower.

For this research, the sample of ASQP data is limited to the three-year period between 1995 to 1997. The reason for this is that take-off times have only been reported since January 1995 in this database.[16]

2.2.2.2 ACARS PILOT REPORTING

1. OUT TO OFF AND ON TO IN DELAY REPORTING

Aggregate data were obtained from this reporting system for the Logan Airport station of a major airline A. This file contains the following information:

Variable	Example	Comments
Operation	ARR	Arrival or departures
Month	9701	
Station	BOS	
Delay code	57	Defined in the aircraft ACARS codes booklet
No. of delays 0-5 min	1	
No of delays 6-16	2	
No. of delays >16	0	
Total	3	
Average length of delay	10	Unclear definition

Table 2-7: Content of airline A Out to Off database

For Logan Airport, these data include 21% of the arrivals and around 52% of the departures. The main causes of delays are reported in appendix 4.5 p. 136.

Item	Value
Total Logan Airport arrivals	12,090
Total Logan Airport departures	12,094
Total reported arrivals	2,599
Total reported departures	6,255
% of reported arrivals	*21%*
% of reported departures	*52%*

Note: 10-month period in 1997

Table 2-8: Percentages of airline A operations recorded in the Out to Off database

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[16] After lengthy debates (see HOUSE OF REPRESENTATIVES [1995]) and against the opinion of most airlines concerned with the release of proprietary network information, the DoT amended the on-time performance disclosure rule to include wheels-off, wheels-on times, and the identification of aircraft by tail number, for the clear purpose of "enabl[ing] the Federal Aviation Administration to analyze air traffic operations and create system models for use in reducing enroute and ramp delays." (Federal Register, Vol. 59 No. 189, September 30, 1994).

2. DELAYS PRIOR TO PUSHBACK

Airline B reports delays prior to pushback. These data follow the same principles and contain the following information:

Variable	Example	Comments
MONTH	7	
DAY	21	
DES	DEN	
FLTNUM	323	Flight number
PAX	110	Number of passengers
BDT ACT SCH	1440	Block departure time actually scheduled
BDT ACTUAL	1441	Actual block departure time
TOSCHED	15	Scheduled time of take-off
TOACT	10	Actual time of take-off
SDR MINUTES	1	Standard Delay Reporting delay, in minutes
SDR ALPHA	CK	Standard Delay Reporting delay code

Table 2-9: Content of airline B prior to pushback delays database

Apparently, the eight first variables are automatically reported through the ACARS system, and may only include random errors due to the ACARS system[17]. The two "Standard Delay Reporting" variables are *voluntarily* reported by pilots, with all the uncertainty involved in such a manual process. Despite these discrepancies, valuable insights can be gained by looking at this data.

12,468 flights have been recorded in this system. Of these, 5,766 have their delays reported and explained. These 5,766 flights account for 88% of the delays that occurred prior to pushback (109,231 minutes out of 123,262). However, only 58% of these delays are recognized as explicated by the delay code associated (71,743 minutes). This is probably due to the fact that only one delay can be recorded by flight. The main causes reported by these pilots are described in appendix 4.5 p. 136.

Item	Value
Total Logan Airport departures (ASQP)	12,405
No. of records for the airline	12,468
No. of canceled departures	468
No. of departures with delay reported	5,766
% of departures with delay reported	*46%*

Table 2-10: Percentage of airline B operations reported in "prior to pushback" ACARS database

These data come from *voluntary* pilot reporting. They have thus flaws:

(1) Delays are not necessarily reported when they are large; there is no rule.

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[17] See appendix 4.4 p. 128 for the validation of ASQP (ACARS) data.

(2) Pilots must assign a single delay number to the delay they experience. It is not possible to give two causes and weight them. Categories may not exactly fit the situation that pilots face. They must again make a subjective choice.

2.2.3 Weather data

According to procedures (see HOCKER [1994]) and discussions with supervisors, the pertinent weather components that impact airport operations are the following:

(1) Cloud ceiling and visibility, that define different *categories* of "Instrument Meteorological Conditions" (IMC) and "Visual Meteorological Conditions" (VMC), and *weather minimums* (defining whether operations can be carried on on two close runways at the same time, and what equipment an aircraft needs).

(2) Wind speed and direction: headwind is sought because it is safer and reduces runway occupancy time.

(3) Precipitation (slower speed) and in general occurrence of bad weather (snow, fog, thunder, etc.)

Both daily and hourly data could be obtained for this research.

2.2.3.1 DAILY WEATHER DATA

Daily weather data are collected for the automatic weather station No. 725090, Boston/Logan International (725090 KBOS BOSTON/LOGAN INTL & MA 4222N 07101W 0020). Discrepancies can be found for some parameters beginning in July 1996 because of the "transition to METAR format for transmission of observations". They follow the format described in appendix 4.2 p. 126. The following variables are of interest to this research:

Variable	Explanation
YEAR	The year
MODA	The month and day
VISIB	Mean visibility for the day in miles to tenths. Missing = 999.9
WDSP	Mean wind speed for the day in knots to tenths. Missing = 999.9
MAXSPD	Maximum sustained wind speed reported for the day in knots to tenths. Missing = 999.9
GUST	Maximum wind gust reported for the day in knots to tenths. Missing = 999.9
PRCP	Total precipitation (rain and/or melted snow) reported during the day in inches and hundredths; will usually not end with the midnight observation--i.e., may include latter part of previous day. .00 indicates no measurable precipitation (includes a trace) Note: Many stations do not report '0' on days with no precipitation--therefore, '99.99' will often appear on these days. Also, for example, a station may only report a 6-hour amount for the period during which rain fell. See Flag field for source of data.
SNDP	Snow depth in inches to tenths--last report for the day if reported more than once. Missing = 999.9. Most stations do not report '0' on days with no snow on the ground--therefore, '999.9' will often appear on these days.
FRSHTT	Indicators (1 = yes, 0 = no/not reported) for the occurrence during the day of: Fog ('F' - 1st digit). Rain or Drizzle ('R' - 2nd digit). Snow or Ice Pellets ('S' - 3rd digit). Hail ('H' - 4th digit). Thunder ('T' - 5th digit). Tornado or Funnel Cloud ('T' - 6th digit).

Table 2-11: Content of the daily weather database

Only seven days are missing (1089 records out of 1096 days) for the period 1995-1997.

2.2.3.2 AUTOMATIC HOURLY WEATHER DATA

Hourly weather data are available at a low cost at the Northeast Regional Climate Center. They contain the following variables:

Variable	Comments
DATE	date (MM/DD/YY)
HOUR	hour (eastern standard time)
SKY	sky cover (tenths: 0=clear; 10=cloudy)
CEIL	cloud ceiling (hundreds of feet: 140=14,000 feet, UNL or -99 = unlimited)
VIS	visibility (miles)
WDIR	direction wind is blowing from (degrees from true north: 90 for east, 180 for south, 270 for west)
WSPD	wind speed (mph)
WX	weather codes (see codes below)

Weather codes

T Thunderstorm	S Snow	F Fog	BD Blowing dust
Q Squall	SP Snow pellets	IF Ice fog	BN Blowing sand
R Rain	SW Snow shower	GF Ground fog	BS Blowing snow
RW Rain shower	SG Snow grains	K Smoke	BY Blowing spray
ZR Freezing rain	IC Ice crystals	H Haze	ZL Freezing Drizzle
L Drizzle	IP Ice pellets	D Dust	A Hail
- precipitation light		+ precipitation heavy	

Notes: There are no symbols for tornado, or waterspout. These phenomena are spelled out completely. Precipitation intensities are indicated as: (-) light; (no sign) moderate; (+) heavy. The intensity indicator follows the precipitation symbol. No intensity is reported for hail (A) or ice crystals (IC). -99 = missing or unreported.

Table 2-12: Content of the automatic hourly weather database

The hourly granularity is often needed to understand what happened on the airport at a certain time. For the period 1995-1997, some discrepancies can be found in these data. In reviewing these variables, we have to note:

(1) SKY	Sky data are available only for 1995 and 1996, and their reporting has changed substantially between the two years: 75% of the 1996 data equal to "-99", mixing unlimited cover and unreported data.
(2) CEIL	Ceiling data are fairly consistent in 1995 and 1996, but are not yet available for 1997.
(3) VIS	Visibility data do not seem biased either, except for the fact that, starting April 1, 1996, visibility higher than 10 miles is reported as "10 miles".
(4) WDIR	Wind direction data are consistent for the 3 years examined.
(5) WSPD	Wind speed reporting changed on April 1, 1996, from a 1-minute average to a 2-minute average. This makes the end of 1996 and 1997 less windy than before.

(6) WX Weather codes are comparable for 1995 and 1996, but a new reporting method was introduced in 1997.

In conclusion, the following hourly weather data are currently available for Logan Airport:

Variable	1995	1996	1997
SKY	✓	✓ (many unreported)	
CEIL	✓	✓	
VIS	✓	✓	✓
WDIR	✓	✓	✓
WSPD	✓	✓ (bias)	✓ (bias)
WX	✓	✓	✓ (less)

Table 2-13: Content of the currently available hourly weather database

2.2.3.3 MANUAL HOURLY WEATHER DATA

It is finally worth noting that hourly Automated Surface Observation Stations (ASOS) reports can be downloaded manually for a specific date in the last months from the NOAA National Data Center.

The following URLs give access to these data:

- http://www.nndc.noaa.gov/usa.htm
- http://www.nndc.noaa.gov/cgi-bin/nndc/phase2.cgi (WBAN #14739 is BOS) for unedited hourly observations
- http://www.nndc.noaa.gov/cgi-bin/nndc/ph2_lcd_v2.cgi for unedited monthly hourly observations.

2.2.4 Future data

As presented in the previous sections, all existing databases that relate to airport operations have major flaws thus reducing the value of historic performance analysis. It is logical that the ATC system has privileged the provision of timely information on the exact position of each flight rather than the recording of aircraft operations and delays since its rationale has always been the avoidance of collisions.

Yet, traffic management has also become a key objective of this system[18]. Traffic management is a big consumer of data. Better forecasts and decision support tools especially need early information on departure flights, before pushback and during ground operations. Two prevailing trends are described below indicating that this lack of data should not

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[18] A proof being given by the progressive change in terminology, from Air Traffic Control to Air Traffic Management.

last for too long. They also motivate the research described in chapter 3, although it had to be based on the limited ASQP dataset.

2.2.4.1 AIR TRAFFIC CONTROL MODERNIZATION

The modernization efforts currently under way will provide many new sources of data. For instance, tracking of all aircraft and ground vehicles has been a requirement for new airport surface radars. For instance, in the Airport Surface Traffic Automation (ASTA) system preliminary design, the FAA was considering many technologies[19] that could eventually provide the exact position of each mobile on the airport (D-GPS, surface-mounted loop sensors) and which data link to use (Mode S transponders, ACARS reporting system, a new VHF data link). Similar projects are being carried on in Europe in the area of "Surface Movement Guidance and Control Systems" (SMGCS)[20].

2.2.4.2 AIRLINE COOPERATION

As described in section 2.2.2.1, ASQP data are based on messages that are automatically sent to each airline when aircraft start to move (brakes are released) and take off. Since these messages are already sent, airlines consider that they could easily be made available in real time in filtered form to each control tower[21].

Airlines' information systems contain a lot of information on the status of each flight that could be used in real time to improve airport operations forecasts. This idea has been prototyped at Atlanta Hartsfield Airport in the framework of the Surface Movement Advisor project (SMA) described in section 2.3.3.3. Another example is provided by the ACARS pilot reports presented in section 2.2.2.2 (p. 65). The federal government may even find it cost-effective to invest in improvement of airlines' avionics in order to get better data[22]. In conclusion, new data on ground movements will be available soon and will make planning much easier.

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[19] See Aviation Week, December 16-23, 1991 and January 10, 1994 for a demonstration of Martin Marietta's concept for ASTA. Aviation Week, November 4, 1996 describes NASA's Taxiway Navigation and Situation Awareness (T-NASA), part of the Terminal Area Productivity program, aimed at poor weather operations.

[20] See for instance Dassault Électronique's RAPSODIE radar and HARMONIA concept, now implemented at Paris Orly, Norfolk, Virginia and Dubai.

[21] According to the Collaborative Decision-Making NAS Status Information subgroup.

[22] See CHARLES [1995].

2.3 DECISION SUPPORT TOOLS IN AIR TRAFFIC CONTROL

2.3.1 Motivation

The FAA 1997 ACE plan justifies the development of Air Traffic Management Decision Support Systems replacing manual procedures for many reasons:

- "Greater collaboration of dynamic airspace management on problem resolution;
- Coordination among local, national, and international traffic flow managers;
- Increased use of airports by assisting in arrival sequencing and spacing, merging streams of traffic, and assigning aircraft to runways;
- Enhanced monitoring, strategy development, and NAS performance measurement;
- International harmonization of data;
- Improved acquisition and distribution of flight-specific data;
- Information updates for static and dynamic data (e.g., route structures, NAS infrastructure status, special use airspace restrictions, aircraft positions/trajectories);
- Improved accommodation of user preferences through improved traffic flow management, conflict detection/resolution, sequencing, and optimal trajectories;
- More flexible airspace structure by reducing boundary restrictions and creating dynamic sectors; and
- Automated information exchange between aircraft and decision support systems."

While the language of this plan is very general, the development of Decision Support Systems remains legitimate given the dynamic non-linear behavior of the NAS. This behavior, while difficult to measure[23], has been observed frequently. Operations are similar from one day to the next. Actors learn to handle them better, and computers could help them even more since operations are drawn from limited sets.

2.3.1.1 AIR TRAFFIC FLOW MANAGEMENT

The conviction that the tools helping controllers manage aircraft flows can both be built and have a positive impact on NAS operations was forged at the beginning of the 1980s when the FAA put an emphasis on *nationwide traffic flow management* by organizing the Air Traffic Control System Command Center (ATCSCC)[24] located in Herndon, Virginia. The ATCSCC is concerned with the management of nationwide traffic problems and the coordination of traffic management decisions taken at the lower level of en-route centers.

The direct motive for this system was the large increase in controller workload induced by President Reagan's 1981 decision to lay off 11,000 controllers on strike. The most profound reason was found in the recognition that serious traffic problems could occur if key airport had their capacity reduced. Since then, Traffic Flow Management (TFM) aims at

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[23] See COCANOWER & VOSS [1997] for a not very convincing presentation.

[24] The ATCSCC was previously called "Central Flow Control Facility" (CFCF).

"match[ing] dynamically air traffic demand with the available capacity of airports and airspace sectors, on a day-to-day basis, in a way that minimizes delay costs or impacts" (ODONI [1994]).

The current systems revolve around the concept of *Ground Delay Programs* (GDP) that are implemented by the ATCSCC whenever future capacity is expected to be substantially lower than scheduled arrival demand[25]. If needed, flights bound for the congested airport are issued Estimated Departure Clearance Times (EDCTs) and Controlled Times of Arrival (CTAs). They are delayed before takeoff to level down the demand at the destination airports.

Although the ATCSCC is now used as the primary tool to deal with serious congestion problems, it has not benefited from solid R&D but has been developed and constantly modified over the last 15 years. EDCTs must be calculated using a model of the tradeoff between ground delays and airborne hold that takes into account the stochasticity of both capacity and demand. Among others, it is for instance necessary to take into account how airlines react to these GDP delays: they often cancel and/or substitute important flights to reduce these costs.

ATCSCC's practice has been criticized as being too conservative, a position which has led to the introduction in 1995 of Managed Arrival Reservoirs (MAR) in the terminal area of airports under GDP: if the GDP is cancelled because capacity and/or demand return to normal, aircraft in this reservoir take instantly profit of this new situation.

Similarly, these centralized decisions do not take into account airlines' objectives. Because of connections between flights, airlines usually prefer a reliable system than a system that minimizes delays but disorganizes their operations. FAA has recently acknowledged this problem and now supports the so-called Collaborative Decision-Making (CDM) program that aims at providing an environment for facilitating the coordination between airlines and the ATCSCC. This program has first developed an information network to improve the management of GDPs through the exchange of data on cancellations and on each airline's reallocation of arrival slots.[26]

2.3.1.2 THE ADVANCED AUTOMATION SYSTEM

During the entire course of the 1980s, FAA invested in an in-depth modernization project named "Advanced Automation System" (AAS). Never completed, this project has had multiple negative impacts on the agency, including loss of credibility within the industry, severe criticisms from Congress, waste of billions of dollars and stepping up of controllers' inflexibility. While the analysis of this failure is not the subject of this thesis, it is

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[25] Precisely, if individual delays are less than 30 minutes and only concern surrounding centers, they are issued locally by en-route centers. If ground delays are expected to exceed 30 minutes for more than 2 hours, GDPs are national and implemented by the ATCSCC.

[26] See HALL [1998].

important to keep in mind that recent automation systems have had to the environment created by this initiative.

Besides, it is important to mention that the FAA continues to include its modernization programs within Decision Support Systems projects, as appears on table 2-14. While the opportunity for DSS development must be acknowledged within these programs, the complexity involved in each of them should prevent the agency to put a too large innovation burden on them as it wrongly did with the AAS.

Program	**Facility affected**	**Program purpose**
En Route Automation Program	En Route/ Oceanic	[...] replace aging [...] equipment
Tower Automation Program	Airport	integrate new and existing safety systems in a consolidated automation platform with a common computer/human interface.
Automated Radar Terminal System (ARTS) improvements	Terminal	Developing terminal software.
Standard Terminal Automation Replacement System (STARS)	Terminal	Improving automation capabilities in the terminal environment.
Traffic Management System (TMS)	All	Integrated hardware and software to accommodate modern computing and communications technology
En Route Software Development	En Route/ Oceanic	Software changes
Flight Service Automation System (FSAS)	Flight Service Stations	Simplify flight plan filing and NOTAM briefings.
Oceanic Automation Program (OAP)	Flight Service Stations, En Route/ Oceanic	Automation infrastructure for oceanic operations.
Oceanic Air Traffic Automation	En Route, R,E&D	R,E&D to lay foundation for new initiatives (free flight in oceanic airspace)
CTAS prototype	Airport, Terminal	Prototype
Advanced Traffic Management System (ATMS)	Flight Service, Airport, Terminal, En Route	Reconstructed to focus on building collaborative decision making and decision support systems that allow collaboration with industry
Surface Movement Advisor (SMA)	Airport	Coordinate surface activities through an unprecedented sharing of operationally-critical surface movement operations
Traffic Alert and Collision (TCAS)	Aircraft/ Aircrew, Terminal, En Route	Independent airborne collision avoidance capability.
Aviation System Capacity Planning	Airport, Terminal, En Route	Development of an overall capacity strategy, of tools that aid in the formulation of strategy to reduce delays
Airport Pavement Technology	Airport, R,E&D	Integrated method for pavement design
Airborne Information for Lateral Spacing (AILS)	Airport, Aircraft/ Aircrew	Safe reduction of lateral spacing requirements during Instrument Meteorological Conditions.

Source: 1997 ACE Plan, FAA, pp. 99-100.

Table 2-14: Decision Support Systems programs according to the FAA

2.3.2 CTAS: the nuts and bolts of decision support tools

At the same time as the AAS components were falling apart, a new initiative was launched at NASA research centers at the beginning of the 1990s after many years of basic research. The Center TRACON Automation System (CTAS) and comparable tools developed elsewhere[27] are good examples of what decision support tools can achieve in the Air Traffic Control environment. Although it can now be considered as a success, the few points below will show how its design process has been tormented. It is essential to keep in mind this experience when developing new tools.

CTAS focuses on providing computer-generated advisories to help approach controllers manage arrivals on large airports. It consists of 3 automation tools:

(1) The Traffic Management Advisor (TMA) which helps plan the most efficient landing order and assign landing times for all arrivals while they are still in the en-route center.

(2) The Descent Advisor (DA) which gives advisories to the en-route controller to achieve a safe and efficient descent to the TRACON metering gate.

(3) The Final Approach Spacing Tool (FAST) which provides heading and speed advisories that allow for the reduction in spacing between landings.

The history of the CTAS project is particularly interesting because it provides lessons in developing new Decision Support Systems. Out of this rich history that can be traced through a long list of research papers and publications, it is important to mention:

(1) The approach taken, "design a little, test a lot": simulations and operational tests have been conducted in parallel with design because of the complexity of airspace operations, and have allowed to focus on the highest-potential subsystems.

(2) The shift from an enumeration algorithm to a fuzzy-logic rule-based sequencing system, caused by the necessity to adapt to controllers demands. This change reduced the efficiency of the system, but not excessively because the benefits mainly come from reduced spacing and better runway allocation. This however meant accepting suboptimal behaviors.

(3) The constant attention to controllers' reactions[28] (human factor): for instance, a Controller Acceptance Rating Scale (CARS) was designed to record controllers' opinions on the system as an essential measure of its efficiency.

(4) While CTAS advisories could be easily sent to cockpit flight management systems, it is currently designed as a completely independent advisory that supplements current ATC procedures. If CTAS fails, it has no effect on radar displays.

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[27] Like COMPAS (Computer-Oriented Metering Planing and Advisory System) in Germany or MAESTRO (Moyen d'Aide à l'Ecoulement Séquencé du Trafic avec Recherche d'Optimisation) in France.

[28] This was specifically underlined in a recent NRC report, WICKENS [1998].

Although the prototypes at Denver En-Route Center and Dallas-Fort Worth TRACON are widely acknowledged as successes, development of the system has been slower than planned[29]. It is doubtful that the FAA will be able to "implement TMA at 15 ARTCCs between the years 2002 and 2004, and passive FAST at 22 TRACONs between 2002 and 2006"[30].

2.3.3 Approaches to airport operations

Various reasons explain why departure operations have not received the same attention as arrivals. First, since airborne holding induces fuel consumption and controller workload in a particularly busy airspace, arrivals have always the priority over departures that occur only "between arrivals". Second, the overall philosophy is that flights can be delayed as much as necessary *before takeoff*, and not in the air. This includes flight preparation and traffic management decisions (like GDPs, see section 2.3.1.1). In consequence, departure operations are very uncertain. "One of the most unpredictable portions of a flight is the time the aircraft spends on the ground, prior to take-off."[31] Frequent delays happen before departure from a gate, and even more frequently, on the taxiway system before takeoff[32]. Both modeling and analysis of departure operations are thus complex tasks that have only recently been considered. This section describes the main projects that have dealt with airport operations in the U.S. and Europe.

Historically, many scholars have shown the benefits of class sequencing. Already in a 1971 report, Gordon RAISBECK [1971] suggested using computers to sequence aircraft since "the demand for sequencing is greatest when volume of flow is greatest". Since then, many papers have been published on sequencing algorithms. The real-world applications have however been quite limited.

2.3.3.1 THE CURRENT PRACTICE OF DEPARTURE OPERATIONS IMPROVEMENT

Airport Capacity Enhancement plans show how the FAA improves departure operations. In the last 5 years, 4 airport capacity teams recommended such modifications. These modifications are described below in table 2-15. The practice clearly focuses on airspace/airport organization to facilitate sequencing.

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[29] "If all goes well, we should see CTAS at a number of air traffic control facilities where there is a need for it in five to six years" (H. Erzberger, leader of the project, in Aviation Week, November 23, 1992).

[30] FAA-ASC [1997], p. 98.

[31] FAA-ASC [1997].

[32] See section 2.2.2.2, p. 47 for examples of pilot reports.

Airport	Suggested improvement
Philadelphia ($12.9M annual savings)	**Remove departure fix restrictions.** "If all aircraft presently operating at PHL were allowed to operate free of miles-in-trail departure fix restrictions beyond optimal aircraft spacing, there could be a reduction in annual delays."
Cleveland ($4.9M)	**Eliminate departure route restrictions.** "At CLE, departures are currently restricted to 10 nm in trail for like-type aircraft on the same route."
Dallas-Fort Worth ($14.2M)	**Allow simultaneous jet departures on close parallel runways during VFR operations.** "The Capacity Team noted that there will be more need for increasing departure capacity than arrival capacity as traffic increases, because the new runways will be used primarily for arrivals."
Portland (?)	**Build departure pads on the ends of runways 10R/28L, 28R.** "This project would improve the flow of ground traffic and reduce taxi interference and delays. Expanding the staging areas would enable controllers to sequence successive departures more efficiently by allowing departing aircraft to bypass aircraft in departure queue."
($39.5M)	**Immediate North divergent turn for turbo props in both flow directions.** "Current noise abatement procedures allow for immediate south divergent turns. North [...] divergent turns would allow the tower controller to fan turbo prop departures in a manner that would expedite departure situations."

Sources: Airport Capacity Enhancement plans.

Table 2-15: Departure improvements suggested in Airport Capacity Enhancement plans, 1993-1998

2.3.3.2 THE DEPARTURE SEQUENCING ENGINEERING DEVELOPMENT MODEL

The Departure Sequencing Engineering Development Model (DSEDM) was designed for the FAA by CSC in 1993-95 to better control departure flows from the South California basin airports. It provides departure sequences to tower controllers, traffic management specialists, and supervisors based on inputs from:

- Traffic management specialists
- Tower controllers (through computer displays)
- Proposed departure times
- Fix flow
- Gate to runway taxi times
- Flight information "Z" messages from the host computer (FZs, AFs, RZs, BZs, DZs), including ATCSCC Estimated Departure Clearance Times (EDCTs)

The DSEDM scheduler, based on a relational database hosted in the ARTCC, generates suggested departure times for flights departing from active DSEDM runways and crossing DSEDM fixes. In addition, a "Data Reduction and Analysis" tool can provide traffic management specialists with various reports from data recorded in the DSEDM.

In order to "help traffic managers manage sector workload and regulate traffic by ensuring that the number of aircraft controlled at any one time does not exceed a predefined level of system capacity"[33], this tool schedules departure releases from selected airports in the South California region.

1. PRINCIPLES OF OPERATIONS

"The DSEDM regulates sector controller workload through the use of fix flow rates, minimum window sizes (MWS) and minimum window flight counts (MWFC)". Controlling for these numbers is sufficient to keep the number of aircraft handled by a sector controller at a manageable level.

It must be made clear that strict scheduling (understood as scheduling in discrete slots such as every 2 minutes) on a given fix imposes precise departure times from the ground. This added constraint on ground traffic increases the potential for missing departure windows. Thus, the DSEDM can use a mode under which it is possible to give more flexibility to ground operations by allowing "bunching", i.e. by not imposing explicit separation at the fix.

To select the level of bunching, the TMU specialist controls the MWS and MWFC parameters. The MWS specifies the smallest permissible window size within which aircraft will be scheduled. Not less than MWFC aircraft will be scheduled within a MWS window. Decreasing MWS reduces bunching since the DSEDM checks that the flow rate does not reach its maximum in any of the windows. Increasing MWFC can increase bunching as it forces more flights into the window.

2. FUNCTIONAL REQUIREMENTS

The main processing capability requirements of this project are:

- **Maintain restrictions on departure fixes,** expressed in aircraft/hour over the fix. It is possible to bias this restriction towards specific airports (that are thus less affected than others by the restriction) and to define high priority airports (whose flights receive less delays if they are expected to arrive at the same time as low priority airports flights).
- **Process departure event changes.** 7 departure statuses are defined: proposed, cleared (route clearance not ready for pushback, included in demand calculations), ready[34] (tower requests to wait), competitive (departure time entered by the TMU controller), taxi (currently taxiing to its runway), lineup (waiting for departure clearance in taxiway lineup), active (actually departed). The tower controllers are at most expected to manually enter changes from "proposed" to "cleared" (when the flight receives its route clearance) and from "cleared" to "taxi" (when it is cleared to pushback). If Pre-Departure Clearance (PDC) is available, the first task is not necessary.

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[33] CSC [1993].

[34] In the tower user's manual, this status is called "gate hold" and described as "not clearly defined" (CSC [1993], p. 2-19). Similarly, the "ground delay" status is described as "undefined"...

Change from "taxi" to "lineup" is automatic, based on the Earliest Possible Departure Time (EPDT). When the NAS activity status is changed to "active", the flight is automatically changed to "active" too. Changes between these statuses are often possible in case of delay.

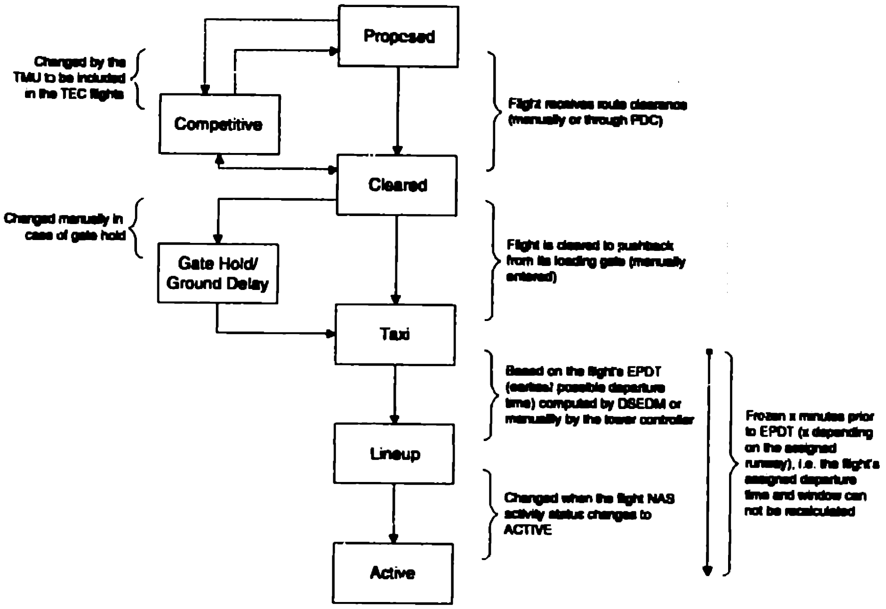


Figure 2-11: Departure flight statuses defined in the DSEDM project

- **Generate departure schedules:** computing airport schedules to suggest departure release times. This is done in 4 steps:
  - (1) *Creation of an initial departure schedule* that includes actual and estimated aircraft pushback times and the application of minimum takeoff separations. This leads to Predicted Departure Times and Calculated Times of Arrival for each fix considered.
  - (2) *Determination of restriction networks* to identify the "restriction networks" caused by this demand and other expected flights.
  - (3) *Computation of fix schedules:* builds fix arrival time windows that will respect the restrictions and at the same time allow for some flexibility in fix and airport departure scheduling.
  - (4) *Computation of airport schedule:* once consistent fix schedules are calculated, these are translated into runway departure times. The process is reiterated until ground restrictions are met (the time windows already answer to most ground restrictions).
- **Monitor DSEDM plan** to periodically optimize the schedule. This function determines whether reoptimization or rescheduling should occur.

3. DISPLAYS

The ARTCC and TRACON TMU specialists have access to 5 displays:

(1) **Monitor display**: information on flights departing from a specific airport/ crossing a specific fix; they can be sorted by departure status, non-DSEDM flights can be added or modified.

(2) **Fix flow forecast display**: graphical display of the number of aircraft projected to cross each DSEDM departure flow fix for the next 1-hour period. This demand is shown for each 15-minute period.

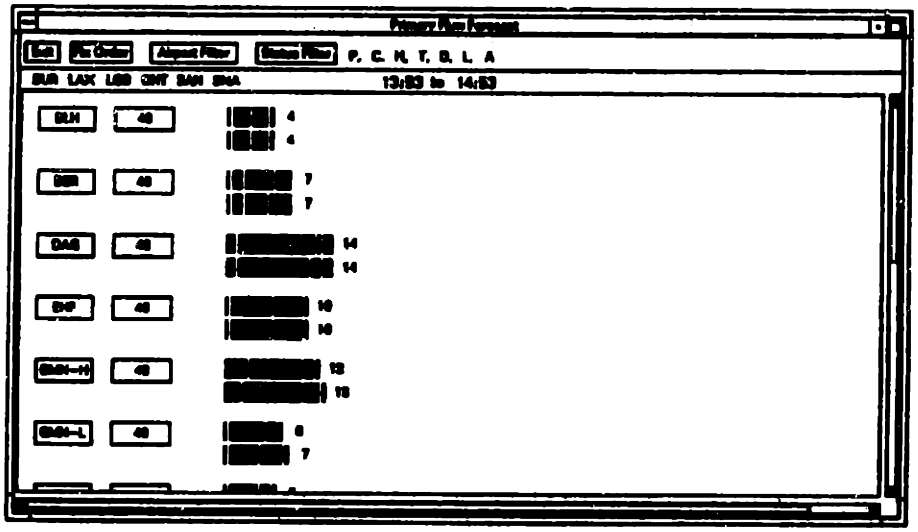
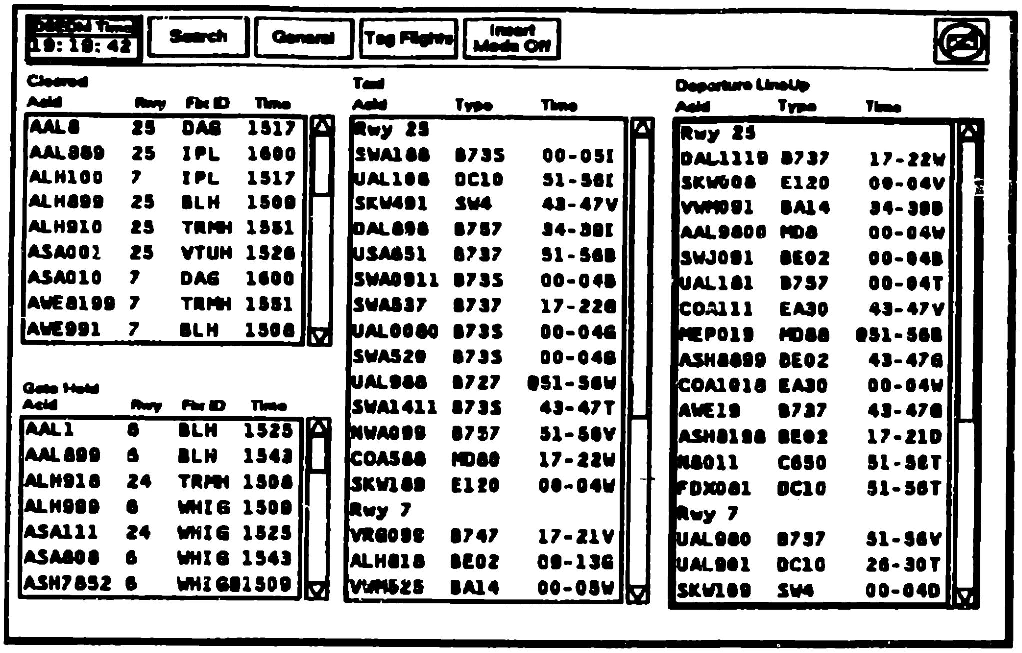


Figure 2-12: Fix flow forecast display, DSEDM project

(3) **Current ground delay statistics display**: provides current and historical delay information for any DSEDM airport or flight

(4) **System status display**: current values of the DSEDM system parameters, communication status of each participating DSEDM tower (including demand bias and priorities between airports).

(5) **Primary fix flow forecast alert**: flashes when the alert threshold is exceeded on the primary fix. In the alert mode, clicking on the icon shows the primary fix flow forecast display.



Cleared

Acid	Rwy	Fix ID	Time
AAL8	25	DAG	1517
AAL889	25	IPL	1600
ALH100	7	IPL	1517
ALH899	25	BLH	1509
ALH910	25	TRMH	1551
ASA002	25	VTUH	1528
ASA010	7	DAG	1600
AWE8199	7	TRMH	1551
AWE991	7	BLH	1508

Gate Hold

Acid	Rwy	Fix ID	Time
AAL1	6	BLH	1525
AAL899	6	BLH	1543
ALH918	24	TRMH	1508
ALH989	6	WHIG	1509
ASA111	24	WHIG	1525
ASA808	6	WHIG	1543
ASH7852	6	WHIG8	1509

Taxi

Acid	Type	Time
Rwy 25		
SWA188	B735	00-05I
UAL108	DC10	51-56I
SKW491	SW4	43-47V
DAL898	B757	34-39I
USA851	B737	51-56B
SWA0911	B735	00-04B
SWA537	B737	17-22G
UAL0080	B735	00-04G
SWA520	B735	00-04G
UAL988	B727	051-56W
SWA1411	B735	43-47T
NWA099	B757	51-56V
COA588	MD80	17-22W
SKW189	E120	00-04W
Rwy 7		
VRG098	B747	17-21V
ALH818	BE02	09-13G
VWM525	BA14	00-05W

Departure LineUp

Acid	Type	Time
Rwy 25		
DAL1119	B737	17-22W
SKW008	E120	00-04V
VWM091	BA14	34-39B
AAL9800	MD8	00-04W
SWJ091	BE02	00-04B
UAL181	B757	00-04T
COA111	EA30	43-47V
MEP019	MD88	051-56B
ASH8899	BE02	43-47G
COA1018	EA30	00-04W
AWE19	B737	43-47G
ASH8198	BE02	17-21D
N8011	C650	51-56T
FDX081	DC10	51-56T
Rwy 7		
UAL980	B737	51-56V
UAL981	DC10	26-30T
SKW189	SW4	00-04D

Figure 2-13: Touch screen display used by the Ground Controller to change flight status

The ATC tower specialist uses a touch screen display to perform the following operations:

(1) Move flights in the system, mainly between the 6 control windows corresponding to the 6 possible flight status: proposed, cleared, ready, taxi, final lineup.

(2) Update flight, runway and airport data.

(3) Override the DSEDM-generated departure sequence by inserting a flight anywhere in the departure sequence ("taxi" or "lineup" status).

(4) Swap flights that are handled by DSEDM (i.e. with the same runway and no manual CDT), without impact on the schedule.

The DSEDM system is an interesting example of implementation of departure planning tools in control towers. Collecting good information on the times when flights reach the various departure statuses[35] opens many windows of opportunity both for analysis and optimization. Nevertheless, the choice of touch screen displays may not be appropriate since it requires much additional work from controllers, especially during high workload periods (when they need advice). Besides, it remains unclear as to what scheduling algorithm was used and on which DSEDM-collected data it was relying.

The system was apparently turned down a few months after implementation, mainly because it did not generate substantial delay reduction but increased controllers' workload.

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[35] We can agree with the basic categories defined in this project, yet some other statuses (gate hold, for what reason) require refinement.

Since it was apparently envisioned as a preliminary design of the Departure Sequencing Program, a program that is still supposed to be included in the new En-Route center displays and take care of departure sequencing, one must be pessimistic on this current (confidential) FAA program.

Europeans also plan the development of sequencing and metering tools integrated in the new Air Traffic Control platforms[36].

2.3.3.3 THE SURFACE MOVEMENT ADVISOR: A SIMPLE BUT EFFICIENT SYSTEM

Like CTAS, the Surface Management Advisor (SMA) program is the fruit of a collaboration between FAA and NASA. Very few publications are currently available on this project, probably because of its youth[37] and simplicity.

SMA functionalities are limited to the distribution of airline data in FAA facilities, and FAA data in airline facilities. Precisely, 19 SMA displays are connected by a computer network to a server that interfaces with NAS data (radar tracks, flight plans), airline data (from the Flight Information Display System (FIDS) that shows flight status to passengers, the OAG, and Delta Operating Center), and airport/ramp tower data.

The tower screens usually show the following information:

(1) Average "push-to-off" times, based on the latest operations

(2) Departure queue information

(3) Aircraft currently pushing back from gates

(4) TRACON arrival lists

(5) Quick look of the "recommended departure split"

In general, the idea is to make available to the tower the revised estimated time of arrivals and departures[38] from the airport, and the planned cancellations, so that controllers can better forecast short-term demand.

Airline screens show:

(1) Arrival lists

(2) Current airport configuration

(3) Total number of aircraft scheduled to depart in the next 4 15-minute periods

(4) Departure rates for each active runway

(5) Statistical information (airfield activity, etc.)

---

[36] See STONER [1995].

[37] The project started in late 1994, and a 90 days operational evaluation was organized in February to May 1997. Funding has apparently been low since then.

[38] Specifically, for the field test at Atlanta Hartsfield Airport, Delta Airlines provided a message to SMA 6 minutes before a flight was ready for pushback.

On the airline side, SMA can indicate exactly when a flight enters the TRACON, arrives on final approach and touches downs. These data do not appear on the ASD[39] because it includes only En-Route Center data. Airlines can also benefit from precise estimates of taxi-in (out) times based on assigned arrival (departure) gate obtained from the FIDS.

However simple this system may seem, its prototype in Atlanta has been very successful mainly because it has allowed Delta Airlines' Operating Center to make efficient operational decisions on each of its flights, and manage airport demand to put a calculated pressure on ATC.

2.3.3.4 DLR'S TAXI AND RAMP MANAGEMENT AND CONTROL (TARMAC)

TARMAC is currently developed in Germany by the Deutsche Forshungsanstalt für Luft- und Raumfahrt (DLR). It should be implemented in the years to come at Cologne and Zurich[40] airport. TARMAC aims at the detailed planning of departure operations in order to efficiently meet strict departure separations on a *tight* taxiway system: these European airports can not afford large departure pads to accommodate many potential departures. Thus, capacity is currently low because aircraft have to wait at the runway threshold for the necessary separation with leading aircraft on their Standard Instrument Departure Route. Besides, it is necessary to deal with the uncertainty of ground movement times.

To achieve this, the DLR team is designing a computer program that *dynamically* plans runway operations using all updated information on the location of each aircraft, and its likelihood to reach its scheduled runway in time. It is possible to adjust the tool to a different tradeoff between takeoff delays and slot violations (i.e. reduced uncertainty of ground movements through buffering).

A simulation testbed has been developed, but key issues have not yet been addressed in the framework of this project, including:

(1) Design of data-collection systems to monitor all operations

(2) Management of uncertainties in the departure process (taxi-out time have high standard deviation)

(3) Adaptation of controllers (human factor)

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[39] That displays ETMS data, see section 2.2.1.1 p. 59.

[40] Under the name DARTS.

Various conclusions must be drawn from this chapter. First, it has shown the complexity of airport operations, and how the essential concern for controller workload has led to the development of Decision Support Systems.

Second, it appears that, although remarkable progress has been achieved, many operational data are not recorded. The simple exchange of information handled by projects like CDM (p. 72) and SMA (p. 81) is extremely beneficial. All empirical data on airport departure operations used in the publications examined for this research were limited to the data sources outlined in section 2.2.

Finally, Decision Support Systems, either understood in the broad sense of intelligent displays or restricted to the provision of advice to controllers, have been highly invaluable while simple designs have often proved more successful. Human factor, and more precisely, controller workload, has been a key limiting factor in the success of these new systems. The new concept presented in chapter 3 tries to address these concerns.

CHAPTER 3
A TACTICAL CONTROL APPROACH TO DEPARTURE CONGESTION AT LOGAN AIRPORT

In this chapter, models of the departure process from Logan Airport are developed to support automated advice-giving tools that could reduce taxi-out delays. To do so, we proceed in four steps. First, we consider where and how to intervene practically on the departure process. Second, we define and discuss the behavior of six fundamental characteristics of this process (p. 88). We then develop successive models to predict changes in the departure sequences. Finally, we discuss how these models can induce cost savings for the various agents of the Air Traffic Control system.

3.1 LOCUS OF INTERVENTION

Based on the discussion of the previous chapters, it appears that ground movements on the taxiways are only constrained with respect to security and the risk of gridlock. These constraints are met using strict procedures regarding the direction of flows and priorities between aircraft. This does not mean that rerouting of aircraft does not occur but that this organization limits controllers' ability to build specific sequences of aircraft during the departure process. Indeed, ground controllers are good at rerouting aircraft so that they quickly reach their assigned runway despite various obstacles on their way, such as other aircraft pushing back, aircraft assigned to other runways or waiting for their take-off performance data.

Many scholars have shown that good runway sequencing can have a major impact on capacity. The idea is to dynamically build schedules that deal with the major separation constraints without excessively moving away from the First-Come-First-Serve model. However, these concepts have not been implemented in control towers because of work-load issues. Local controllers have developed *ad-hoc* strategies to handle the sequences, either alternating between Standard Departure Routes (see section 2.1.1.1 p. 48) or "bunching" aircraft of the same weight category. Since this sequencing is currently both a low priority objective for the local controllers and a task that they alone handle, most controllers consider that all strategies are equally efficient, and are ready to neglect it when the airport becomes congested.

This explains why it is interesting to investigate how the demand on the runway system can be controlled before aircraft reach the runway where the local controller takes care of them. Since Ground Controllers can be extremely busy when they have to control many aircraft, they can not either construct specific sequences at that time. This is why it is necessary to look even earlier in the departure process: when pilots ask for their clearance to pushback.

The control "at pushback" is not a new idea. At Logan Airport, a position named "gate control" is in charge of the "efficient metering of outbound aircraft". It is however usually not filled. Besides, it is designed to curb the overflow of aircraft that could occur on the taxiway system (or similarly, at the level of the Ground Controller), and not to help build the runway sequence.

This analysis leads us to investigate here the **detailed control of runway operations,** which consists of:

- The sequence of aircraft that reaches each runway. This includes sequencing between weight-based classes and between aircraft bound for different fixes or destinations that are metered.
- The time at which each aircraft reaches its runway. If an aircraft is late, some runway time is wasted. If it is too early, it has to wait for other operations to finish.

By investigating this specific question, we strictly frame the scope of intervention of the projected tool: it is aimed at providing *automated advice at clearance delivery to achieve a "better" control of departure operations*. We will explicit our definition of "better" only in section 3.4, when we examine how these models can reduce congestion. Whatever objective is selected, it can only be implemented if the runway sequence is controlled.

To develop the supporting models, it is only necessary to consider the airport traffic system to the following extent:

(1) Input set	Requests for pushback (time, aircraft type[1], location on the airport)
(2) Output set	Take-off sequence on each runway (time, aircraft type[1], runway)
(3) State set	General airport configuration (runways used, visibility, etc.) Number and order of aircraft of each type that are bound to each runway Queue occurrence

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[1] Again, this type is not limited to weight-based classes but may include final destination, airline and fix.

(4) State transition map	State transition with time as the controller accepts requests for pushback and aircraft start their take-off rolls.

The following diagram better describes the system that is modeled:

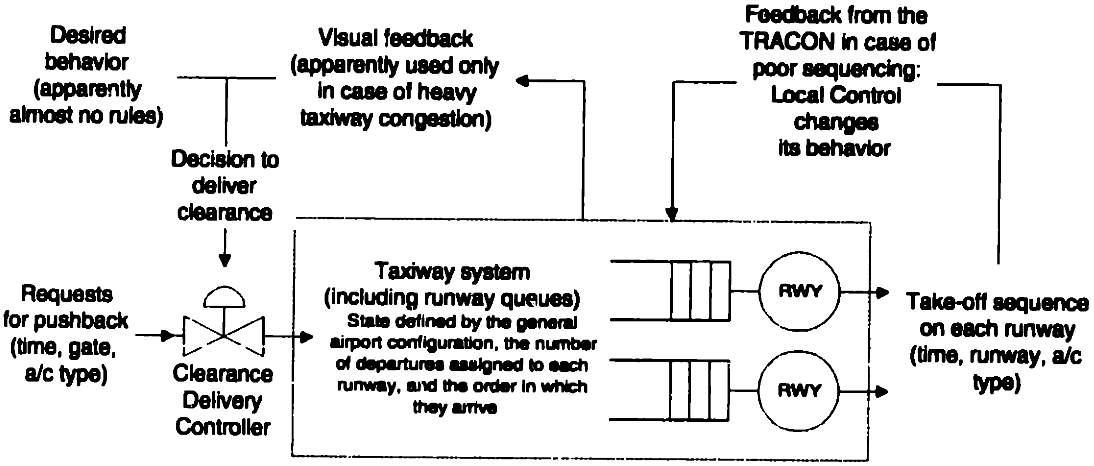

Figure 3-1: Diagram of the current departure process to model

In the current organization described on figure 3-1, there is almost no control at the pushback request. Pilots are always cleared and wait for the Ground Controller to contact them[2]. Besides, there is no "open loop" desired behavior, since the Clearance Delivery controller only checks flight plans details before giving the clearance, without considering sequencing issues. Similarly, there is almost no feedback ("closed loop") from the taxiway system or the TRACON: only in rare cases of heavy congestion, Clearance Delivery blocks aircraft at their gate. Bad runway sequencing does not affect this controller directly since a call from the TRACON is answered by the supervisor and remedial action is taken by the local controllers in charge of the active runways. Sequencing is achieved by the local controller responsible for each runway based on the mix of aircraft that is handed over to him/her.

The planned intervention thus consists of either:

- Simple "open-loop" rules that the Clearance Delivery controller could apply to convert the sequence of requests into a "better" sequence at the runway thresholds, or
- More complex "closed-loop" rules that would consider the situation on the airport (congestion, weather, etc.) and the actual sequences at the runway thresholds.

This is illustrated better on Figure 3-2 below.

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[2] See section 2.1.3, p. 53.

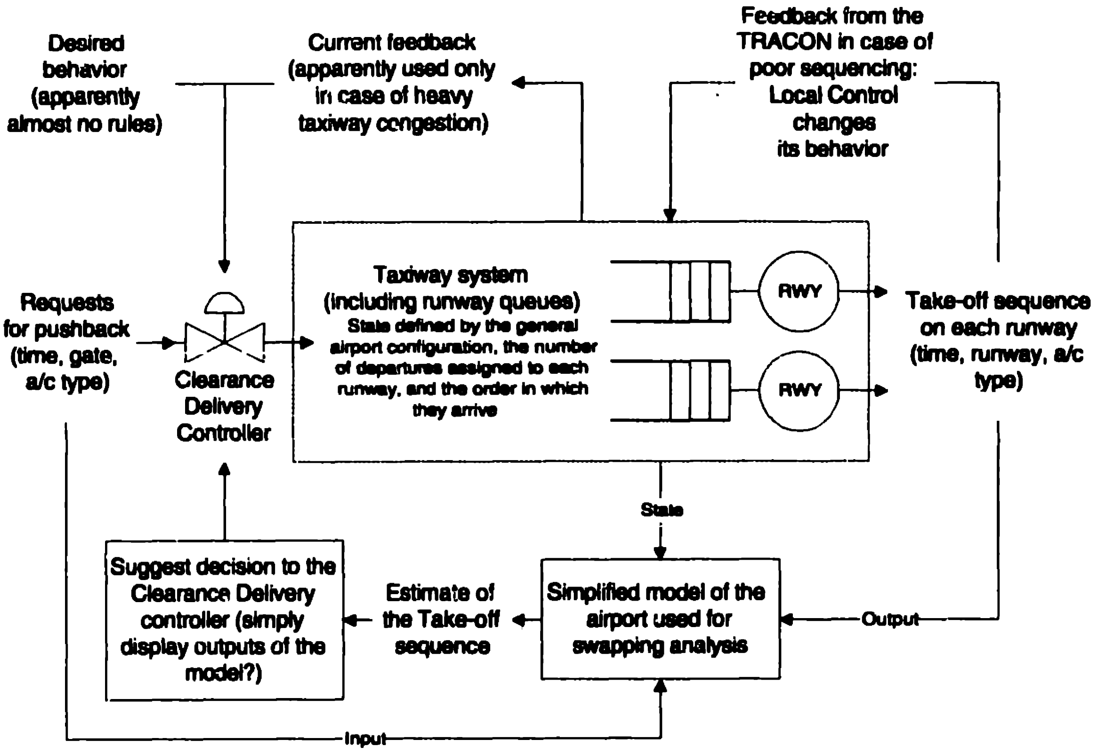

Figure 3-2: Diagram of the system and its interaction with the sequencing tool

3.2 EMPIRICAL CHARACTERISTICS OF THE DEPARTURE PROCESS

3.2.1 *Datasets*

As seen in section 2.2.4, although there are reasons to expect a large inflow of data in the long term, few data are currently collected during the taxi-out section of a flight. The main avenue of analysis is the ASQP database that was described in section 2.2.2 (p. 63). In spite of the fact that it is an historical database, it should be relatively easy to obtain in real-time since it is based on the ACARS messages that are instantly transmitted between each airline's fleet and operations center. It records around 45% of all operations at Logan Airport.

It would also be possible to extract the sequence of takeoffs from the ETMS data (See section 2.2.1 p. 59), but estimates of pushback times for aircraft that are not included in the ASQP remain highly uncertain considering the variety of delays and delay causes affecting pushback times[3]. Since it is difficult to make assumptions on the behavior of these other operations, we thus concentrate on **the sequencing of the jets included in the ASQP.**

Two datasets need to be built in order to develop swapping models. The first one is required to calculate the parameters of the models while the second is used to evaluate the models.

To select these datasets, it is important to list the parameters that must be controlled for. These include:

- The location of the takeoff runways.
- Weather conditions.
- Other conditions affecting operations' efficiency (equipment outage, etc.).

Two other issues need to be mentioned. First, the ASQP database is plagued with a long right-hand tail. It is difficult to qualify these observations as outliers since they either fit in a sequence of severely delayed operations or show the overall stochasticity of the process, which can not be overlooked. To estimate taxi-out times for the CODAS system[4], the highest 25% of the values are excluded.

Second, the performance of the airport evolves over time so that, in general, taxi-out times increase from one year to the next. This is largely due to the growing congestion that affects the entire system and makes Traffic Flow Management decisions more frequent.

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[3] SHUMSKY [1995] discusses this problem in detail.

[4] See section 2.2.1.3, p. 62.

The combination of ASQP and PRAS data (see section 2.2.1.2, p. 60) on the first 3 months of 1997 generates three samples for each of the main "departure zones" on Logan Airport:

(1) The Southwest corner, for 4R, 4L, 9 and any combination of these three runways.

(2) The Northeastern area, for 22L and 22R.

(3) The Eastern section, 33L and 27.

Other operations occur under mixed departure configurations, for instance 4R and 15L.[5]

Departure area of the airport	No. of departures	Percentage
Southwest (4R, 4L, 9)	6,292	27%
Northeast (22L, 22R)	8,492	37%
East (33L, 27)	7,170	31%
Other (mixed configurations)	957	4%
Total departures	22,911	100%
Cancellations	1,033	
Observations in the original sample	23,944	

Table 3-1: Number of departures that traveled through as specific zone of Logan airport, January-March 1997

Identifying periods when operations were not perturbed is a complex task since disruptions come from many different sources. A disrupted departure is defined here as a departure that (1) takes more than 30 minutes to take-off and (2) is followed by a departure that takes more than 30 minutes to take-off within the next 10 take-offs. This second condition is used to select only repetitive delays.

Figure 3-3 shows when these disruptions occur on the entire sample. The concentrations of delays display three shapes:

(1) Limited concentrations: for 15 to 20% of the 90 days, around 9:00 and 19:00.

(2) 2 hour disruptions: these disruptions usually happen around the two peak hours of (1), but specific conditions maintain delays to a high level for a longer period. This occurs for instance on January 24 and 29 or February 2.

(3) Large disruptions: affecting departures during the entire day, like January 11, March 14 or 31.

Most of these disruptions can be explained by the configuration under which the airport operated (27 - 33L or a single runway), or the poor visibility (many lasting disruptions occur during periods with a visibility lower than 1 nautical mile), or by apparent runway closure (identified by a period with many aircraft that have pushback but that do not takeoff). However, a certain number of these disruptions

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[5] For a layout of Logan airport, see figure 1-13, p. 43.

can not be explained by either of these parameters. This is for instance the case of January 2, 1997: the weather was fine (low wind speed, good visibility), the configuration had a high capacity (22R - 22L), but operations were delayed during most of the morning.

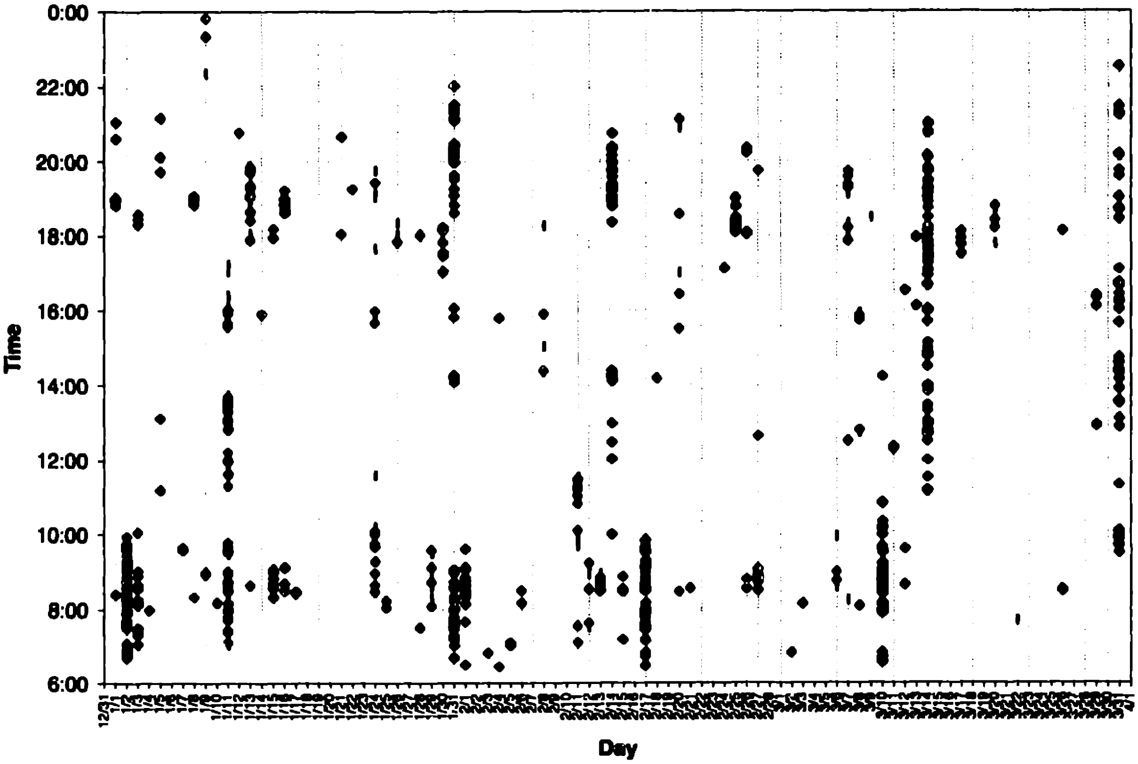

Figure 3-3: Disrupted operations between January and March 1997

To solve this problem, for each airport configuration, the sample is reduced to days without such severe disruptions. After analysis, the Southwest configuration dataset is built by excluding the days with more than 10 disrupted operations under these configurations, excluding the following days:

Day	Disrupted operations (southwest cfgs)	Disrupted operations (all cfgs)	Average taxi-out
1/11/97	38	80	0:33
1/24/97	13	18	0:19
1/31/97	38	50	0:23
2/11/97	18	18	0:17
2/17/97	40	40	0:20
3/14/97	25	68	0:23
3/31/97	37	43	0:25

Table 3-2: Days with more than 10 disrupted operations under Southwest configurations

As a result of this analysis, the first dataset contains 5103 observations. These observations are shown below on figure 3-4. The dark points correspond to disrupted operations as defined previously.

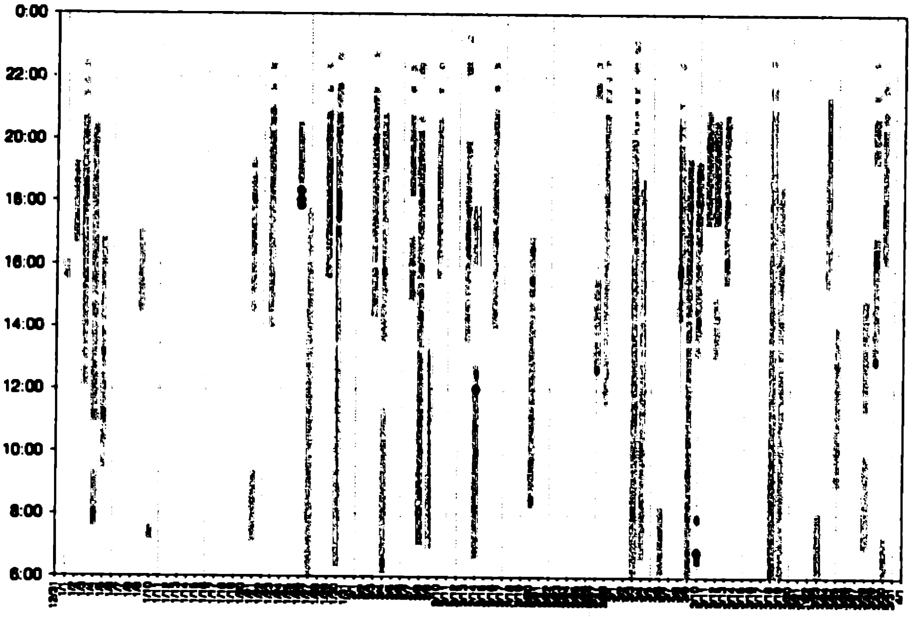

Figure 3-4: Operations included in the southwest sample (in gray) and disrupted operations (dots)

It is necessary to mention that Delta Shuttle operations must be separated from the mainstream operations of Delta airlines because their gates are located with US Airways at terminal B. They are thus close to the Southwest corner and far from the Northeast departure zone.

The same approach is obviously followed in order to develop the validation dataset, on the segment April-June 1997.[6] After selecting the 8,977 operations that occurred under Southwest configurations, it appears that only 117 departures were severely disrupted. This leads to exclude only 3 days from the sample:

Day	Operations under Southwest cfgs	Disrupted operations (all cfgs)	Average taxi-out
4/18/97	277	32	0:20
5/19/97	230	18	0:18
6/18/97	151	12	0:16

Table 3-3: Days with more than 10 disrupted operations in the validation sample

The validation sample thus contains 8,316 departures.

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[6] This segment is selected close to the first sample in order to solve for the progressive evolution of delays over the years.

To close this section on the construction of the datasets, it is important to mention that a validation of the data recorded in the ASQP system was performed at Logan Airport. It is detailed in appendix 4.4, p. 132. It confirms that this database is quite accurate.

3.2.2 Definitions

To characterize the departure process from a large airport, the sample paths for six stochastic processes of interest were extracted from the ASQP database[7]:

(1) The number P(t) of *requests for pushback received at time t*. In this chapter, we assume that it is strictly equal to the number of actual pushbacks recorded in the ASQP database[8].

(2) The number T(t) of *takeoffs that occur at time t*. This value is obtained directly from the ASQP database.

(3) The number L(f) of *aircraft that have been overtaken by flight f when it takes off*. In this research, "overtaken" is defined by the fact that an aircraft has pushed back before f but has not yet taken off.

(4) The number S(f) of *aircraft that overtook flight f when it takes off*.

(5) The taxi-out time TO(t), the time taken by the last aircraft from its gate to takeoff.

(6) The number N(t) of departing aircraft on the taxiway system at instant t. We exclude arrivals from the variable N(t) for two reasons. First, they do not usually affect the order of departures, except when they block pushback operations for some gates. Since this phenomenon of apron congestion is difficult to capture, it seems wiser not to model it. Second, N is more directly connected to the state of departure queues that develop at the runway thresholds. It is clear that the length of these departure queues impacts on the runway departure sequence.

The three figures 3-5 to 3-7 show how these variables evolved between 7:00 and 8:30 on 4 January 1997.

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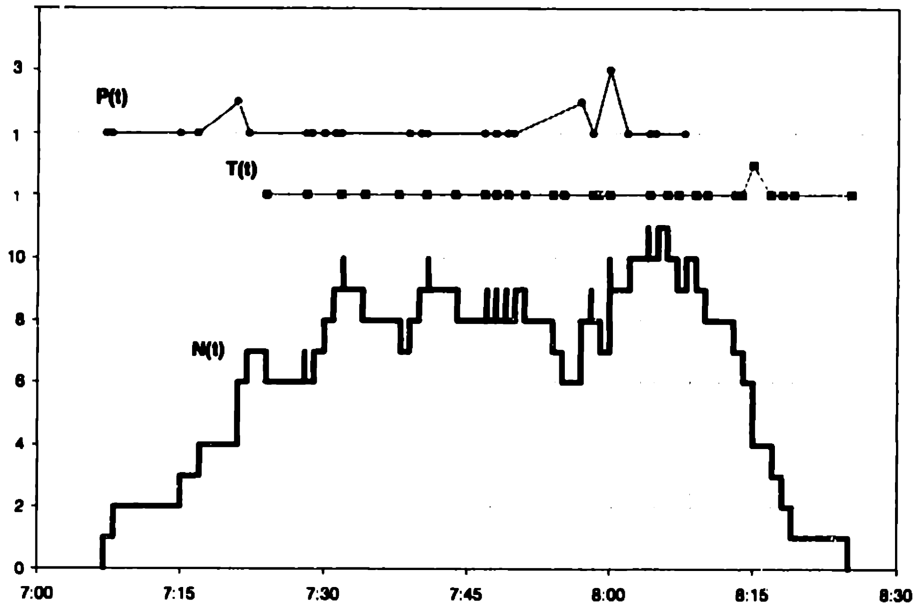
[7] In this research, stochastic processes are noted $\{X(t)\}$ and the underlying variable, $X(t)$. Then, a sample path is $\{(t_0, X(t_0)), (t_1, X(t_1)), \ldots\}$.

[8] Actual pushbacks are defined in this database by the brake release. Takeoff is defined by the release of the weight off the wheels.



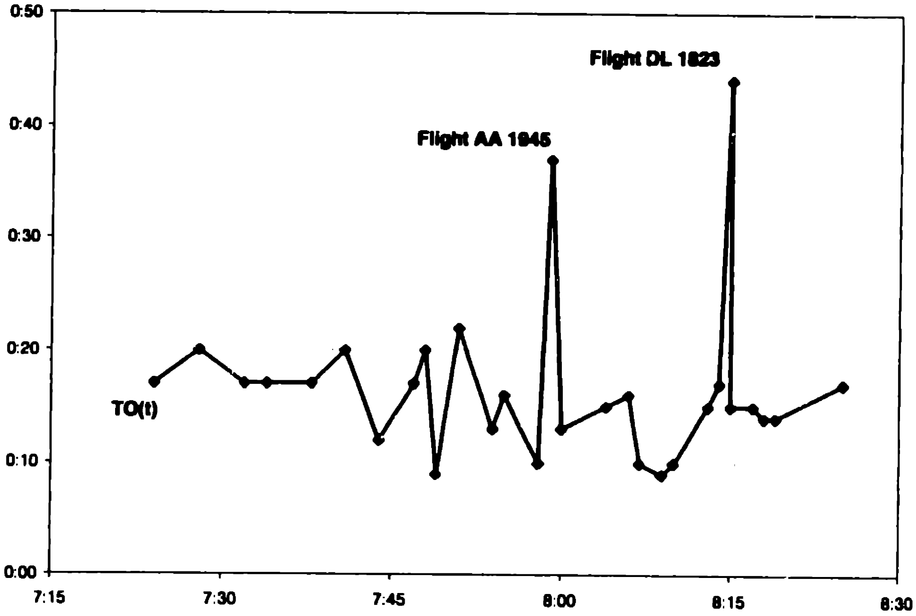
Source: ASQP database, 4 January 1997.

Figure 3-5: Sample paths of {P(t)}, {T(t)} and {N(t)}

If, for each day, is defined $T_P = \{t_{p0}, t_{p1}, \ldots, t_{pn}\}$ ($T_T = \{t_{t0}, t_{t1}, \ldots, t_{tn}\}$) the set of times when P (T) is not equal to zero, we can entirely define the departure sequence with the three stochastic processes $\{P(t)\} = \{P(t_{p0}), P(t_{p1}), \ldots, P(t_{pn})\}$, $\{T(t)\} = \{T(t_{t0}), T(t_{t1}), \ldots, T(t_{tn})\}$ and $\{TO(t)\} = \{TO(t_{t0}), TO(t_{t1}), \ldots, TO(t_{tn})\}$.

Then, with $T = T_P \cup T_T = \{t_0, t_1, \ldots, t_n\}$, $\{N(t)\} = \{N(t_0), N(t_1), \ldots, N(t_n)\}$ is defined by:

$$N(t_n) = \sum_{i=0}^{i=n} \left(P(t_i) - T(t_i)\right) \quad \forall n$$

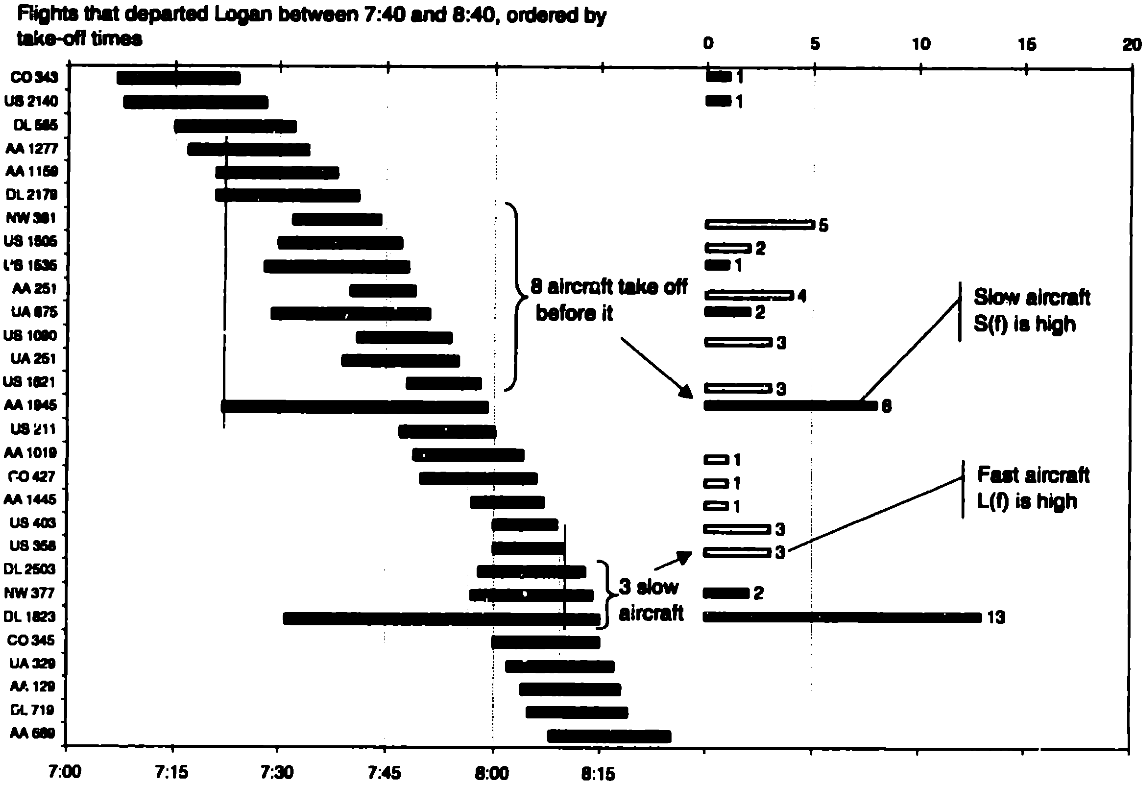


Source: ASQP database, 4 January 1997.
Figure 3-6: Sample path of {TO(t)}

To define the processes {L(f)} and {S(f)}, we simply consider the function F: $f \rightarrow (i, j)$ where f pushes back at t_{pi} and takes off at t_{tj}. We then have:

$$\begin{cases} L(f) = i - j & \text{if } i > j \\ L(f) = 0 & \text{otherwise} \end{cases} \qquad \begin{cases} S(f) = j - i & \text{if } j > i \\ S(f) = 0 & \text{otherwise} \end{cases}$$

The motivation for these two variables is that they characterize two types of flights of interest to this research: the flights that taxi-out slowly and those that taxi-out quickly in comparison with the ones that have departed at roughly the same time from the airport. By construction, for each flight f, at least one of L(f) or S(f) equals zero. The meaning of these measures is presented next page using an example.



Source: ASQP database, 4 January 1997.

Figure 3-7: Sample paths of {L(f)} and {S(f)}

S(f) is the number of flights that overtake f while it taxies-out. On figure 3-5, flights AA 1945 and DL 1823 take more than 30 minutes to take-off. 8 aircraft pushback after flight AA 1945 and takeoff before it. Thus, S(AA 1945) = 8. Symmetrically, US 358 pushes back after DL 2503, NW 377 and DL 1823, but it takes off before these 3 flights. L(US 358) = 3.

3.2.3 Empirical behavior

In this section, the characteristics of these 6 processes are reviewed on the Southwest dataset. It is important to keep in mind that this sample contains only 45% of the departure operations that were performed at this airport under these configurations.

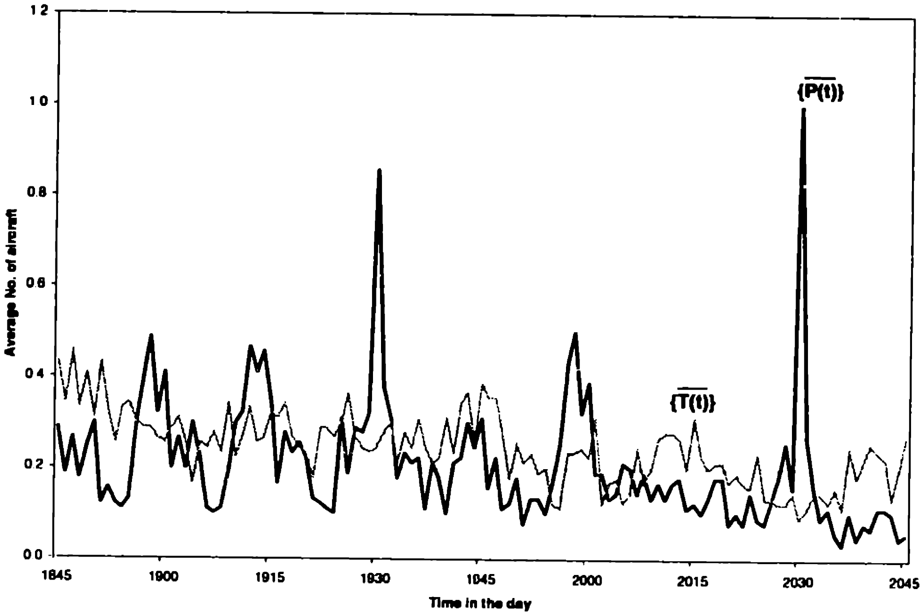
3.2.3.1 THE PUSHBACK AND TAKE-OFF PROCESSES {P(T)} AND {T(T)}

Figure 3-8 shows {P(t)} and {T(t)} averaged over the three-month period:

$$\forall t \quad \overline{P(t)} = \frac{1}{90}\sum_i P_{day_i}(t) \quad \overline{T(t)} = \frac{1}{90}\sum_i T_{day_i}(t)$$

Because of the variability of operations, it is necessary to average these processes for them to show their typical behavior. The original schedule peaks at the round hours (00, 15, 30, 45, etc.) remain, but they are significantly flattened. This is attributable to two causes. First, since many causes can induce gate delay, aircraft that are scheduled for the same hour are in general not ready at the exact same time. Second, we must recall the fact that ASQP data correspond to *actual pushbacks*. This means that the "ASQP sensor" is located after the Clearance Delivery controller[9]. Frequency congestion limits his/her ability to process an excessive number of pushback requests, and thus further flattens the curve.

Then, this curve is translated in time and filtered even more by the various events that occur during the taxi-out phase of a flight, including time spent in a departure queue. Take-off throughput never exceeds 0.4 aircraft per minute[10], i.e., for all operations, the equivalent of 55 departures per hour ($0.4 \div 45\% \times 60$ minutes).



Source: ASQP data, 18:45 to 20:45, January-March 1997 (22,911 observations)
Figure 3-8: Average number of aircraft pushing back {P(t)} and taking-off {T(t)} at each minute at Logan Airport

The shape of these average processes must be opposed to other airports, such as a strong hub like Atlanta Hartsfield. According to Figure 3-9, which shows the same period of the day for Atlanta, this airport operates on a low frequency. The wave of departures, scheduled every five minutes between 18:55 and 19:40, builds during the entire period and

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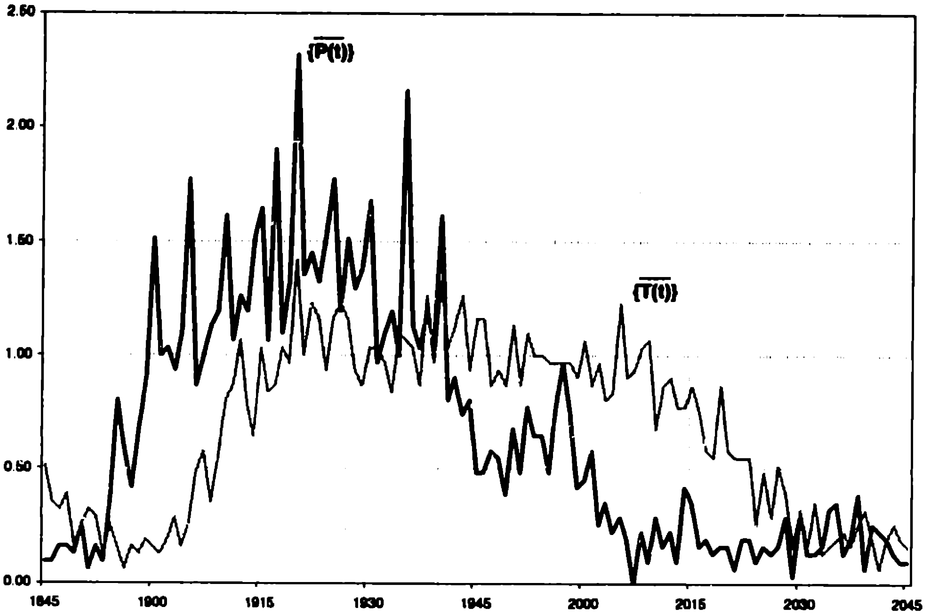
[9] See section 2.1.3.2 p. 54 for more information on the organization of a control tower.

[10] At no time during the entire day. Because of arrivals, the maximum departure throughput is even lower on Figure 3-8.

is flattened and stretched as it reaches the runway system, which appears saturated between 19:15 and 20:05.



Source: ASQP database, Atlanta Hartsfield Airport, 18:45 to 20:45, January 1997 (20,003 observations) Note: The y-axis should not be directly compared with Logan Airport since the ASQP database contains roughly 70% of Hartsfield operations and 45% of Logan.

Figure 3-9: Average number of aircraft pushing back {P(t)}, and taking-off {T(t)} at each minute, Atlanta Hartsfield Airport

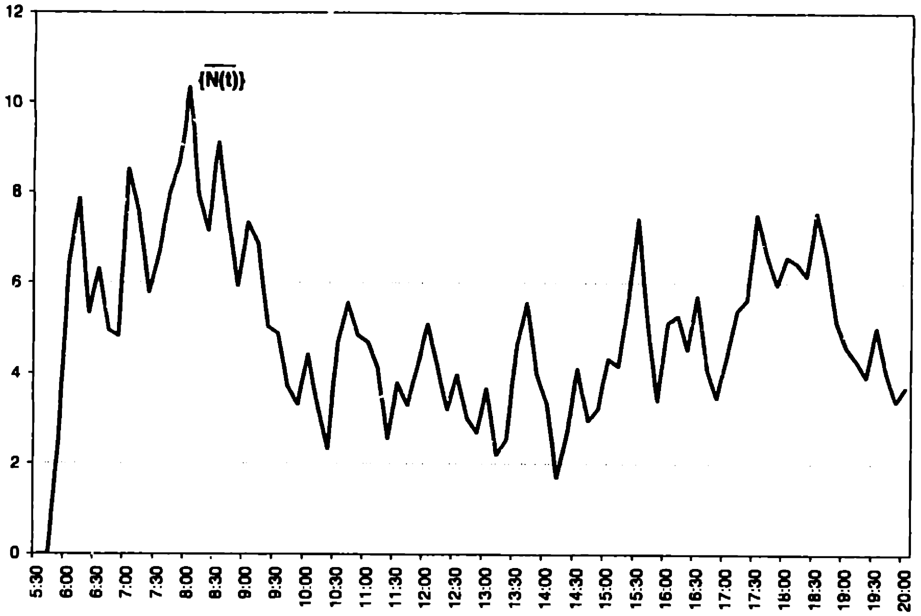
This analysis has a primary impact on the tools developed in this chapter. To the difference of Atlanta, where Delta Airlines saturates the departure capacity during long periods (from 19:10 to 20:10 on figure 3-9), Logan Airport faces a constant demand throughout the day with extreme peaks at the round hours. These high peaks are in any case filtered out by the taxiway and runway system. It is thus useless to have these peaks handled as fast as possible and let them accumulate at the runway thresholds. Metering at pushback makes thus sense at Logan Airport. Following SHUMSKY [1995, 1997], this figure shows that, at Logan Airport, "there is no clear transition between free flow and saturation."

3.2.3.2 THE NUMBER OF DEPARTING AIRCRAFT ON THE TAXIWAY SYSTEM {N(T)}

The incessant oscillations of the two processes {P(t)} and {T(t)} lead the process {N(t)} to constantly change without clear evolutions: unlike Atlanta, there are no defined waves of pushbacks at Logan airport. As a result, runway system saturation is transient. For instance, the averaged process on a one-month period, defined by the equation below, is drawn on Figure 3-8.

$$\forall t \quad \overline{N(t)} = \frac{1}{30}\sum_i N_{day_i}(t) \text{ where } N_{day_i}(t) \text{ is the value of } N \text{ at instant } t \text{ on day } i$$

At peak hours, this figure shows an average 6 to 8 departing aircraft on the taxiway system. It does not seem necessary that the runway system be saturated to handle these 6 to 8 aircraft if they are well spaced.[11]



Note: To be more significant, this figure is not based on the sample but on the entire operations that occurred during the month of January 1997.

Figure 3-10: Average value of $\{\overline{N(t)}\}$ for every 10 minute period of the month of January 1997

In the sample, there are never more than 20 departing ASQP aircraft on the taxiway system. This occurs during bad weather days, especially when the airport needs to be closed.

3.2.3.3 THE NUMBERS OF LATE AND SLOW FLIGHTS {L(F)} AND {S(F)}

On the sample, L and S have usually low values, as appears on figure 3-11. 67% of the flights do not overtake any other flight (L(f) = 0 at take-off time); 21% overtake 1 flight, etc.

This is explained by three factors. First, Logan Airport is a constrained airport: even when three runways are used for departures, their thresholds are all located in the same zone, and aircraft converge towards them using a maximum of 2 taxiways on which they can not overtake each other. Second, the ASQP database contains only 45% of the

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[11] This differs sensibly from sample paths at Atlanta Hartsfield, which often reach high values of N between 20 and 30 aircraft.

departures from Logan Airport. Since these departures are spread along the entire day, they are spaced in time, which reduces the probability of overtaking. Third, no airline controls large sections of the aprons on which it could invert the order of its departures. If some airlines could do so, like United at Chicago O'Hare, their flights would often have higher L and S than observed.

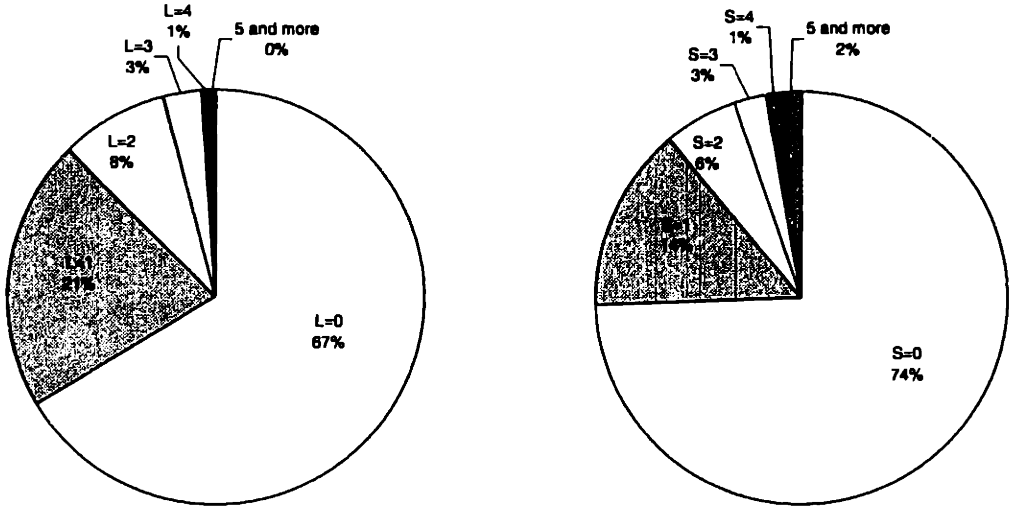
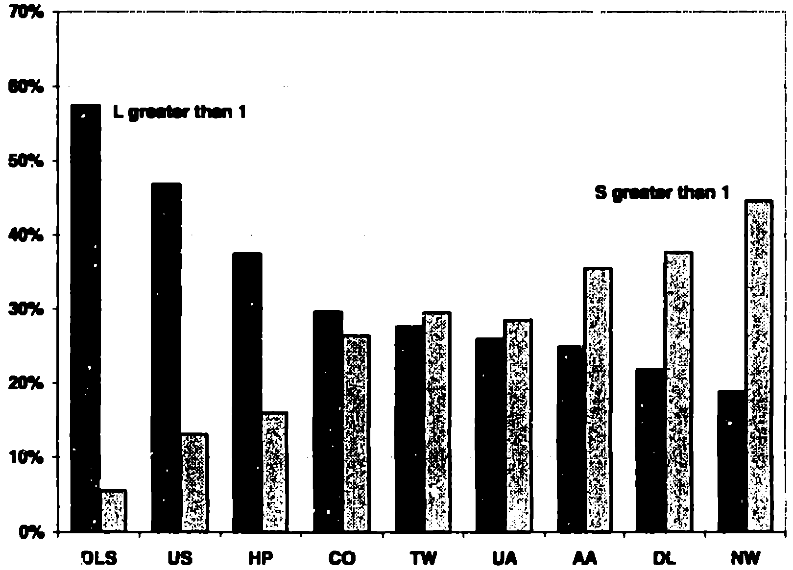


Figure 3-11: Frequency of L(f) and S(f) on the entire sample

As expected, {L(f)} and {S(f)} differ sensibly between airlines. The frequency with which L(f) ≥ 1 and S(f) ≥ 1 for each of the 9 airlines is shown below.



Note: HP refers to America West, DLS refers to Delta Shuttle. (Southwest sample).
Figure 3-12: Percentages of each ASQP airline's departures that "overtake" other flights (i.e. with L(f) ≥ 1), and that "are overtaken" (i.e. with S(f) ≥ 1).

Figure 3-12 shows a significant difference between three airlines (DLS, US and HP) around 35-55% and the other ones, especially NW and DL, that seldom "overtake". Symmetrically, this observation can be made on S: more than 30% of AA, DL and NW flights are 'slow', versus less than 20% for DLS, US and HP.

This ranking fits well the position of each airline with respect to the Southwest corner, shown below on figure 3-13.

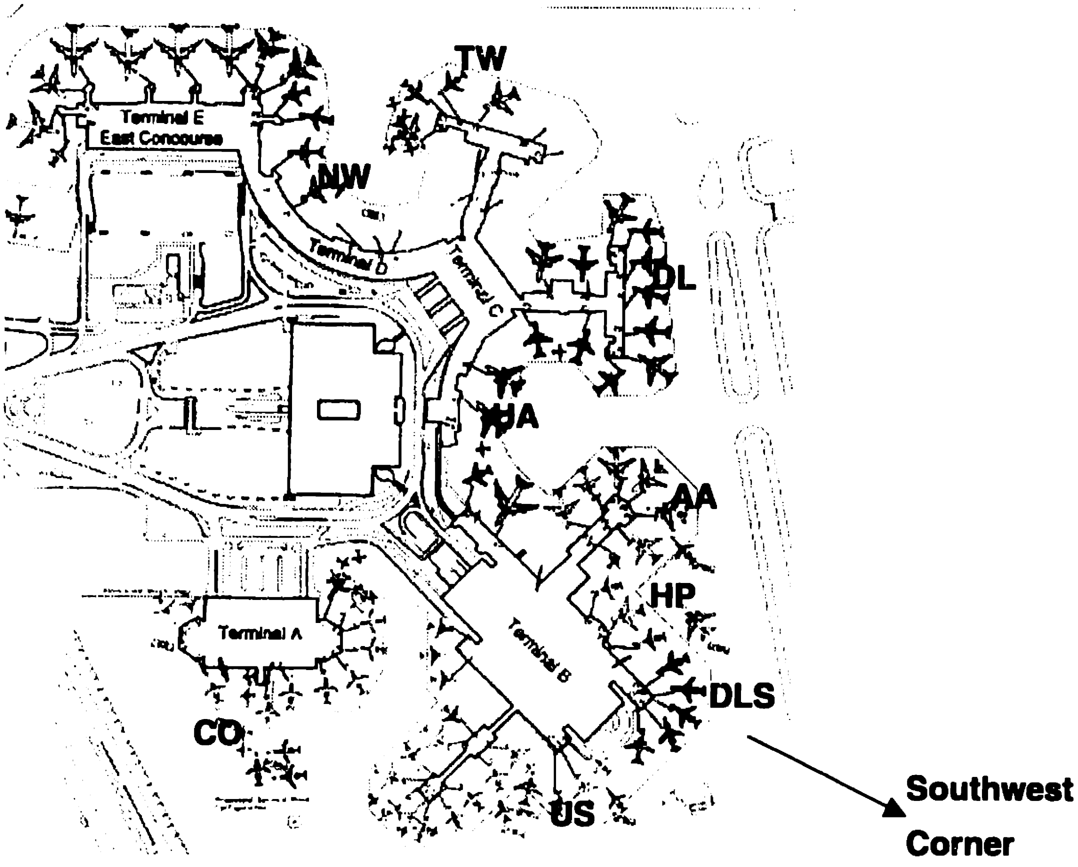


Figure 3-13: Position of the 9 airlines' gates on the airport

In conclusion, while the data contain a lot of noise, there is a clear link between {L(f)} (or {S(f)}) and the airline of the flight f.

3.2.3.4 THE TAXI-OUT TIMES {TO(T)}

The process {TO(t)} is directly obtained from the ASQP data since it is the time taken between *pushback* to *takeoff*. The first point to make is that TO is quite variable: most flights take between 8 and 25 minutes to taxi-out, and the standard deviation is 7 minutes.

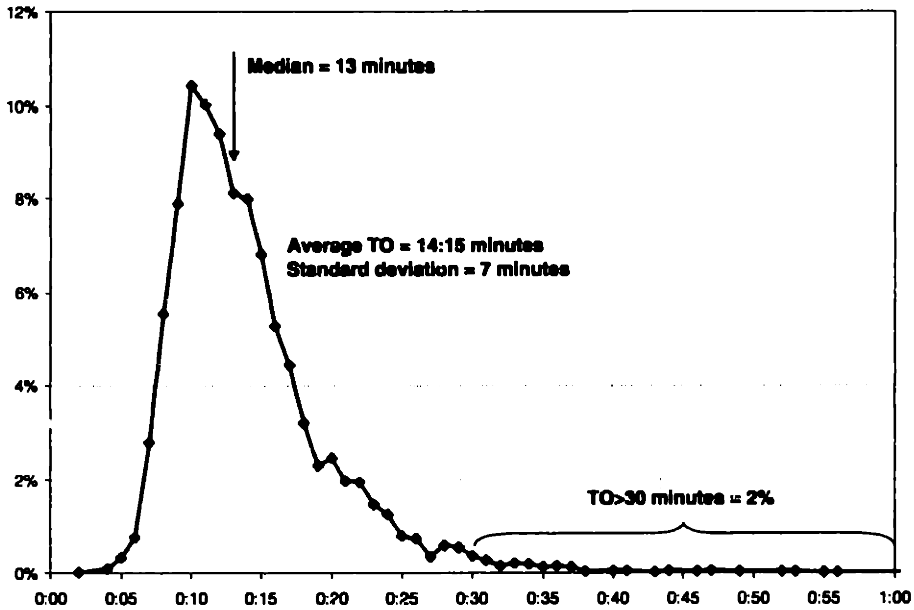


Figure 3-14: Distribution of TO(t) for all flights in the sample

SHUMSKY [1995] has developed sophisticated models of the taxi-out time at Logan Airport. Yet, he could not sensibly improve the forecast accuracy, mainly because of the large number of outliers with high taxi-out times, like flights AA 1945 and DL 1823 on figure 3-6. However, the distributions are significantly different for each airline. On the sample, each airline has the following TO average and standard deviations:

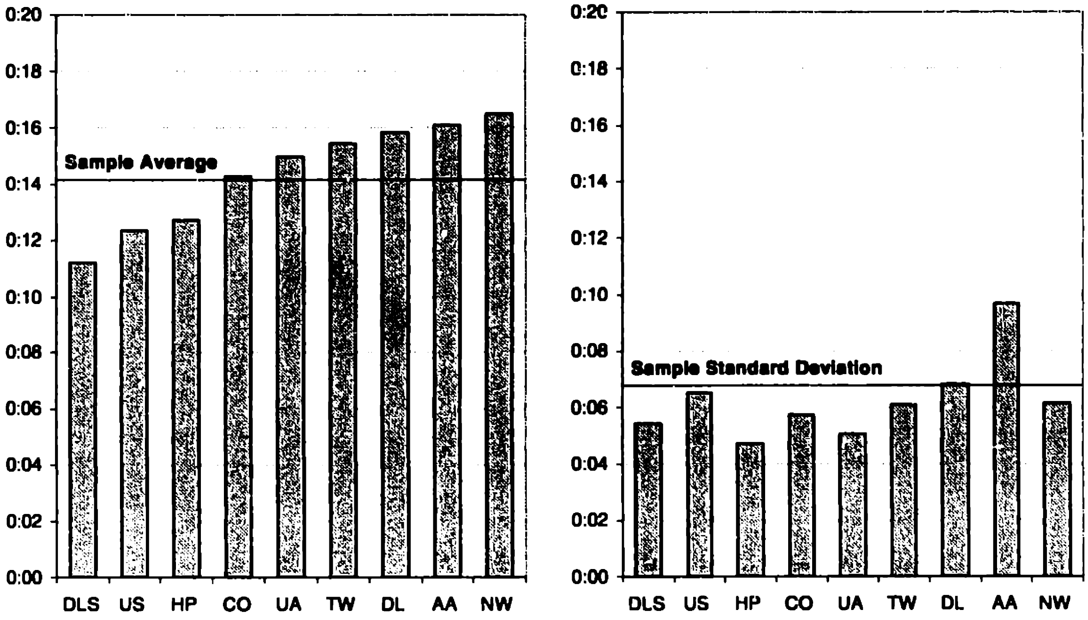


Figure 3-15: Average and standard deviation of TO(t) for each airline

The difference between each of these airlines is not large: except for the 3 fastest airlines, all have an average taxi-out between 14 and 16 minutes. This is explained by the many delay causes and departure queue times that are included in these averages. United Airlines may have a lower standard deviation because a large amount of its taxi-out time is performed with a tow truck, which is probably less variable than travel on regular taxiways. Conversely, American Airlines' figures are affected by the centralization of the takeoff performance data calculation within its Airline Operating Center in Dallas, which induces larger delays. They are also affected by the diversity of operations carried out at Boston: some flights are frequent connections to the main hubs in DFW and ORD while some others are leisure-related heavy jets bound for Miami and San Juan.

3.2.4 Correlations

In the chapter 6 of his thesis, SHUMSKY [1995] develops models of TO(t) by looking at the correlation of this variable with airlines, weather, configuration, congestion, etc. Since the main explanatory factor he found for his static models was N(t) at pushback, we examine in this section the correlation between N(t) and the other variables of interest.

Figure 3-16 shows the correlation between traffic density and taxi-out time.

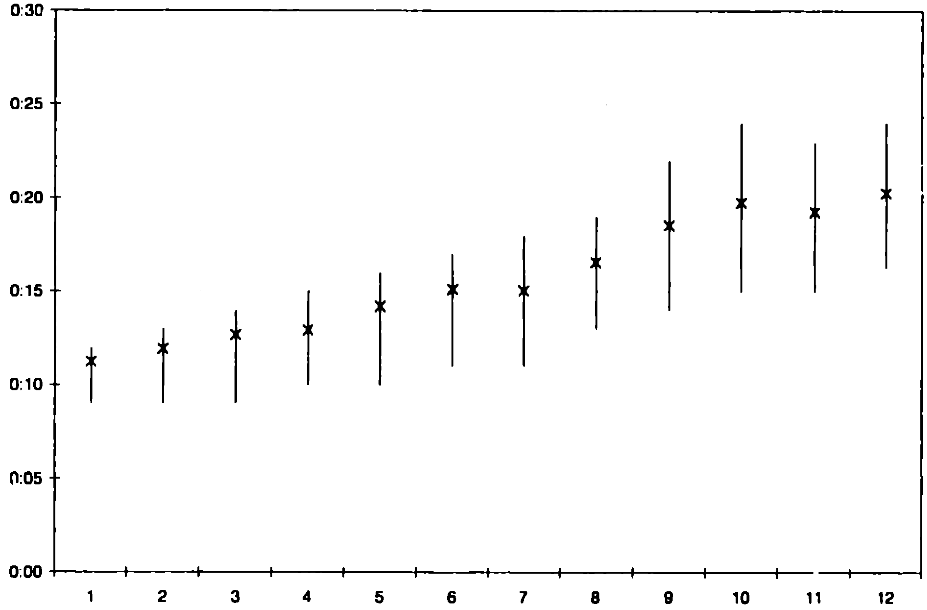
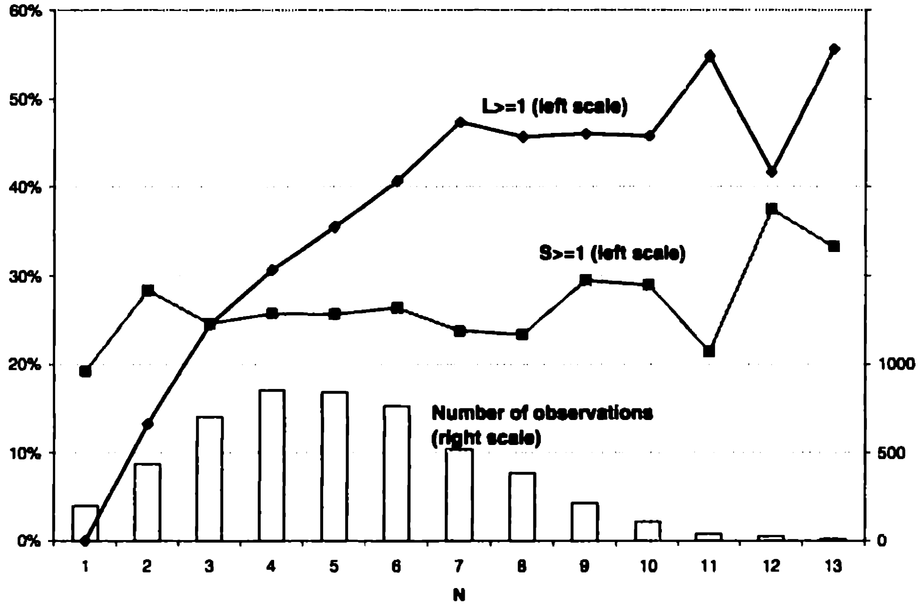


Figure 3-16: Average value, first and third quartiles of TO(t) as a function of N(t) at pushback, Southwest sample

Figure 3-17 shows the conditions under which swapping occurs.



Note: The figures for N≥14 are not included because they are based on a too small sample.
Figure 3-17: Percentage of operations with L≥1 and S≥1 as a function of N

The frequency of "slow" aircraft is independent of congestion, but since there are more opportunities to overtake other aircraft when N is large, the frequency of L≥1 grows with N.

3.3 SWAPPING MODELS

3.3.1 Principles of model development

Considering the complexity of the operations described in the previous section, models' accuracy can be improved along two dimensions:

(1) Including more variables describing the situation at the airport at any time, for instance the runway configuration, weather, airline, etc.

(2) Focusing on specific periods during which the departure process is simpler.

This explains why we follow the procedure described on Figure 3-22. Improvements originate in the analysis of the residuals of the model. These improvements are tested before being used in control strategies.

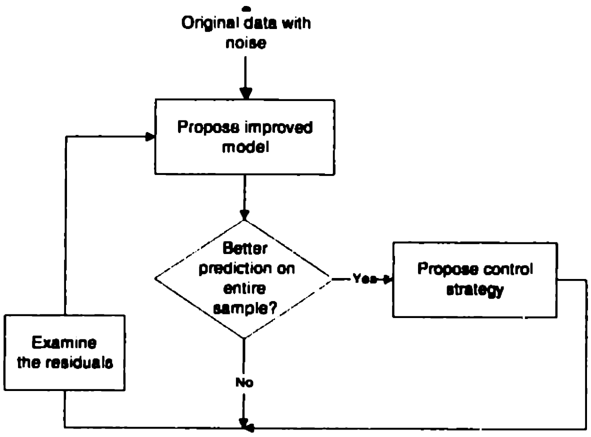


Figure 3-18: Procedure for the development of swapping models

3.3.2 First deterministic swapping model: "dumb"

As a starting point, the first model simply considers that there will be no swapping between pushback and takeoff. It correctly predicts L for 70% of the flights: all the flights that have L=0. Similarly, it correctly predicts S in 75% of the cases. It however predicts both on only 45% of the flights.

3.3.2.1 RESIDUES

The examination of the flights whose swaps are not predicted shows that S is poorly predicted for NW, DL and TW while L is poorly predicted for DLS and US. When looking at the distribution of residues with N, the prediction of S is not biased (just like in the entire sample) but L is not predicted well for all N higher than 7.

3.3.3 Second deterministic model: differentiating by airline

3.3.3.1 CONSTRUCTION

Following the analysis of residues carried in the previous section, it is natural to account for the differences in location of each airline. The first idea thus consists in modeling the difference in taxi-out time between these airlines. To do so, since the distributions are skewed towards high values, it is better to consider the taxi-out times with the maximum likelihood of occurrence. Based on the first sample, this gives the following values under the Southwest configurations:

Airline	AA	CO	DL	DLS	HP	NW	TW	UA	US
Taxi-out time (min.)	12	11	12	7	8	14	15	13	9

Table 3-4: Maximum likelihood taxi-out times observed for each airline

The procedure is then straightforward since these taxi-out times give estimates of take-off times. At each instant t, the take-off sequence is given by:

(1) Consider the N(t)-tuple { (airline, pushback time) }

(2) Calculate { (airline, pushback time + taxi-out time (from table 3-4)) }

(3) Re-order this set by increasing time. This is the expected take-off sequence

At first, this model does not display large improvements. Considering its ability to identify whether a flight will be fast (L≥1) or not (L=0), it gives the following results on the validation sample:

	Real L=0		**Real L≥1**		
Model	**Predicted as such**	**Predicted ≥1**	**Predicted as such**	**Predicted as 0**	**Accurate predictions L**
Dumb	5810	0	0	2506	5810 /8316
Second model	5091	719	1189	1317	6280 /8316

Table 3-5: Predictions of the two first models

S is similarly accurately predicted for 6,375 observations (vs. 6,213 for the dumb model). The ability to predict swaps (L≥1), which is achieved quite often (1,189/2,506 departures) is traded for mistaken forecasts of L≥1 (719/5,810) which thus reduce improvement of the model.

3.3.3.2 RESIDUES

To improve this model, it is thus important to identify the features of the 719 departures that were wrongly expected to swap, and of the 1,317 departures that swapped but were not expected to. Airlines are treated very differently by this model: DLS and HP are always expected to overtake while NW, UA and TW, never.

Airline	L≥1	Of which wrongly predicted as L=0		L=0	Of which wrongly predicted as L≥1	
AA	313	278	**89%**	927	49	5%
CO	221	132	60%	629	107	17%
DL	216	195	**90%**	999	52	5%
DLS	325	43	13%	223	95	**43%**
HP	56	10	18%	112	49	**44%**
NW	77	77	**100%**	481	2	0%
TW	42	42	**100%**	203	0	0%
UA	210	194	**92%**	938	11	1%
US	1046	346	33%	1298	354	27%
Total	2506	1317	53%	5810	719	12%

Table 3-6: Residues as a function of the airline

This model is unable to capture the fact that some NW, TW or UA flights might be faster than flights of airlines located closer to the Southwest corner.

N	L≥1	Of which wrongly predicted as L=0		L=0	Of which wrongly predicted as L≥1	
1				271	0	0%
2	76	38	50%	604	33	5%
3	274	154	56%	885	94	11%
4	384	201	52%	1105	129	12%
5	482	260	54%	1012	137	14%
6	448	221	49%	787	133	17%
7	346	178	51%	528	87	16%
8	205	118	58%	314	48	15%
9	132	59	45%	165	32	19%
10	77	38	49%	77	10	13%
11	51	33	65%	38	11	29%
12	19	11	58%	14	4	29%
13	7	5	71%	9	1	11%
14	4	1	25%	1	0	0%
15	1	0	0%	0		
Total	2506	1317	53%	5810	719	12%

Table 3-7: Residues as a function of N

The model apparently looses some prediction power for high values of N, but the trend is not clear.

3.3.4 Third deterministic model: Airline and N

3.3.4.1 CONSTRUCTION

A simple way to model the impact of N on the taxi-out time is to perform a regression of taxi-out time as a function of N using the average taxi-out time calculated above on figure 3-16.

The regression has a good R^2 of 0.96 and a slope of 52 seconds that is a good estimate of the runway occupancy time. Then, taxi-out time is calculated by picking for each airline the maximum likelihood value for N=4. 4 is chosen because it is the value of N with the largest number of observations. The regression value of 52 seconds is then applied to obtain an estimate of the taxi-out time for each airline under each value of N.

3.3.4.2 PERFORMANCE

The results below are disappointing since the third model does not lead to more accurate predictions than the second model. It is less capable of identifying the fast aircraft but at the same time makes less errors in the other direction, 510 vs. 719.

	Real L=0		Real L≥1		
Model	**Predicted as such**	**Predicted ≥1**	**Predicted as such**	**Predicted as 0**	**Accurate predictions L**
Dumb	5810	0	0	2506	5810 /8316
Second model	5091	719	1189	1317	6280 /8316
Third model	5300	510	689	1817	5989 /8316

Table 3-8: Predictions of the three first models

This result illustrates the tradeoff between the two types of errors that deterministic models face. They either find a large percentage of the fast flights but also wrongly predict many other flights as fast, or make less errors on the first group, but more on the second.

3.3.4.3 POTENTIAL IMPROVEMENTS

Various changes can be considered to improve the quality of the predictions of this model. It is typically possible to take into account more parameters such as destination or weather conditions.

A good example of these potential improvements is shown below on figure 3-19.

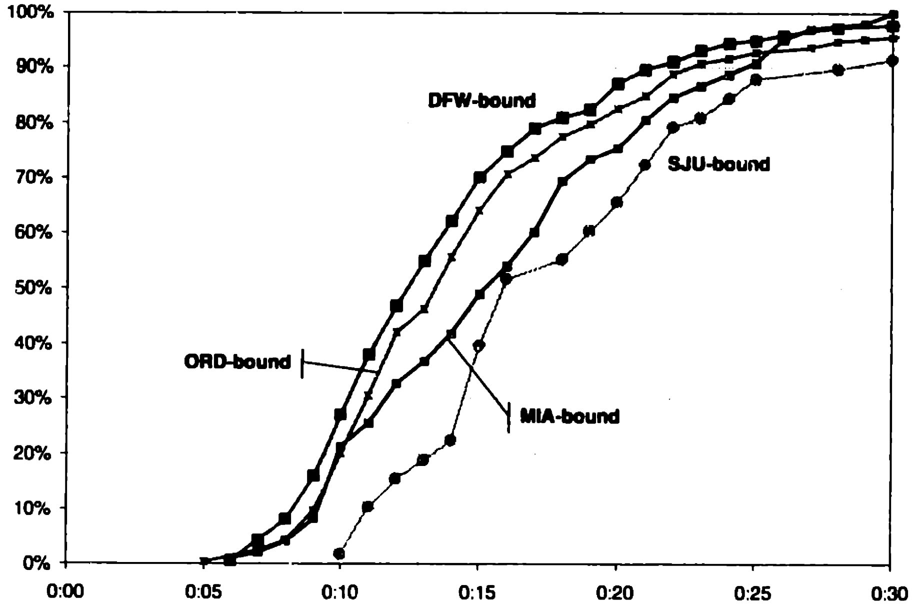


Figure 3-19: Respective cumulative distributions for American Airlines flights bound for 4 destinations

Miami and San Juan-bound flights have cumulative distributions that are sensibly different from O'Hare and Dallas-Fort Worth-bound flights. These flights are handled by larger jets and are often crowded. This has two consequences on taxi-out times:

1. The pilot may need the longer runway 4 Right to take-off. Since this runway is mainly used for arrivals, he/she has to wait for a slot between two arrivals.
2. The exact take-off performance data may be received from the Airline Operating Center with some delays, which forces the pilot to wait a few additional minutes before take-off. This is more frequent because the exact load of these flights is known at the last minute.[12]

While many refinements of this kind can be developed, since the standard deviation of each of these operations remains high, estimates based on such deterministic models will not achieve high accuracy.

A second issue has to do with the measure of swapping. The estimates based on strict overtaking do not take into account how close to each other flights are expected to arrive at the runways. If a deterministic model forecasts that two aircraft will be within 10 seconds from each other, this swapping is actually very uncertain. It is not even valuable since the second aircraft will have to wait at the runway threshold. This is why probabilistic models appear potentially more fruitful.

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[12] These two explanations were confirmed by Mr. Paul Cody, American Station manager at Logan.

3.3.5 Stochastic swapping model

3.3.5.1 PRINCIPLES

Stochastic models are investigated in this section. Two aircraft *i* and *j* pushback from their gates with a time difference d. They are ready to takeoff from the airport at instant t_i and t_j defined by two distinct probability distributions P_i and P_j.

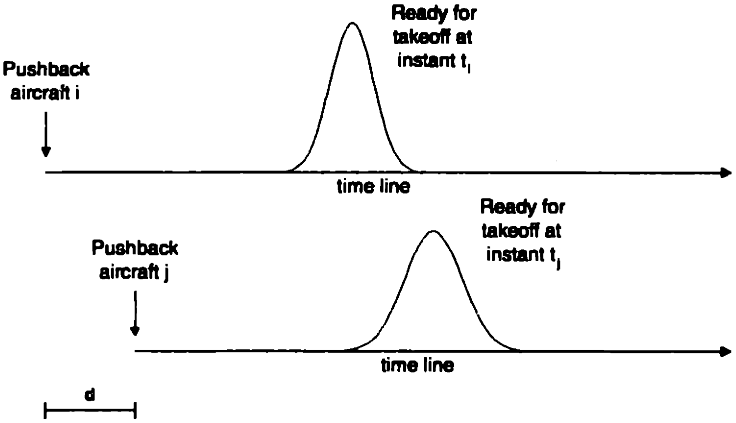

Figure 3-20: Assumptions of the stochastic model

In the case described on figure 3-20, i should takeoff before j unless j is fast and i is slow. The probability of occurrence of the event { j overtakes i } is given by the obvious equation:

$$P(\{ j \text{ overtakes } i \}) = \int P(\{ j \text{ is ready at } t \text{ and } i \text{ is not ready at } t \})\, dt$$

In general, the two events { j takes off at t } and { i takes off at t } are not independent. However, by considering the events { j is ready at t } and { i is ready at t }, it is possible to separate the probabilities since these events can be considered as independent (and only dependent on factors specific to each aircraft or to the situation of the airport when these aircraft depart[13]).

$$P(\{ j \text{ overtakes } i \}) = \int P(\{ j \text{ is ready at } t \})\, P(\{ i \text{ is not ready at } t \})\, dt$$

i.e. $P(\{ j \text{ overtakes } i \}) = 1 - \int P(t_j < t)\, P(t_i < t)\, dt$

This approach can be generalized to n aircraft as long as they pushback in the same environment (i.e. the readiness probability distributions for the following aircraft are not affected by the previous aircraft considered).

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[13] It is reasonable to assume that this situation does not change during the time d between the two pushbacks.

3.3.5.2 READINESS PROBABILITY DISTRIBUTIONS

The previous analysis and Shumsky's work have lead to identify the following factors as essential:

- Gate location (the current best indicator of this is the flight's airline).
- Runways used for takeoff operations: as appears on table 3-1, 96% of all departure aircraft go to a specific point on the airport.
- Departure congestion, characterized by N.

Figure 3-21 shows how taxi-out times are distributed depending on the congestion at pushback. The distributions are relatively well ordered: the taxi-out time increases with N. Besides, it is interesting to note that the standard deviation increases also progressively.

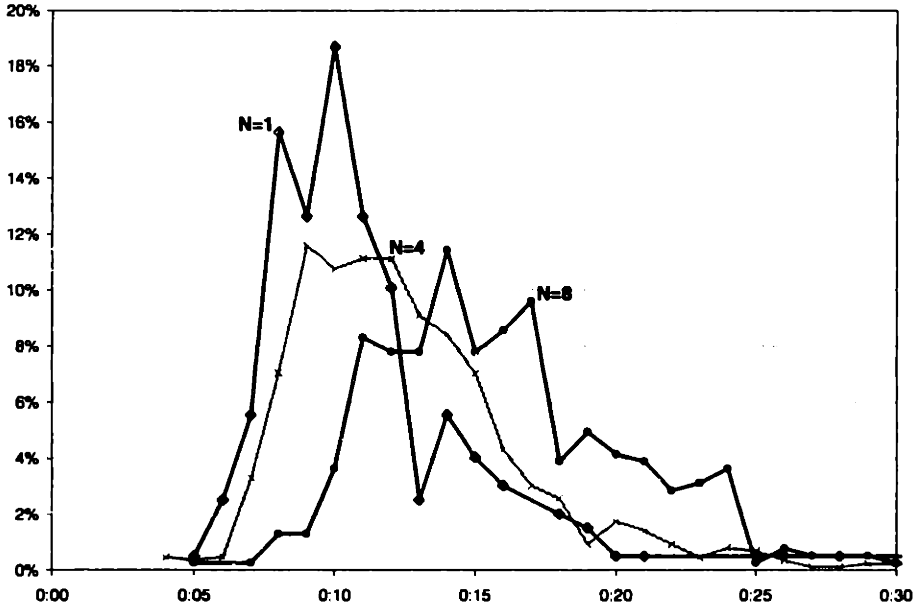

Figure 3-21: Distributions of taxi-out time for 3 values of N at pushback

Taxi-out average and standard deviations are shown below. They confirm this first observation although the exact evolution of the standard deviation is unclear.

N at Pushback	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Total**
Average	0:11	0:11	0:12	0:12	0:14	0:15	0:15	0:14
Standard dev.	0:05	0:04	0:06	0:05	0:08	0:08	0:05	0:06
N at Pushback	**8**	**9**	**10**	**11**	**12**	**13**		**Total**
Average	0:16	0:18	0:19	0:19	0:20	0:18		0:14
Standard dev.	0:06	0:07	0:06	0:05	0:06	0:05		0:06

Table 3-9: Average and standard deviation for the taxi-out time, as a function of N at pushback

When looking at each airline in details, the standard deviations are reduced but remain high because of the right-hand tails. Since the samples of each airline for each value of N are quite small, these samples are grouped together by similar N, to form only 3 sets:

(1) N≤3: low traffic

(2) N between 4 and 7: medium traffic

(3) N≥8: important congestion

These values are selected to form relatively homogeneous sets of operations for each airline. Of course, the third dataset has a high standard deviation and displays a complex shape.

The 3 x 9 samples built by combining these 3 groups and the 9 airlines have complex shapes similar to the ones described on figure 3-21. Using normal distributions to approximate these shapes, it is not appropriate to directly use the observed mean and standard deviation because of the long right-hand tail. To deal with this issue, the distributions are constructed using only the lower values of the observed distributions up to the maximum likelihood and approximating them with a Normal distribution. When there are several maximum likelihoods, or when it is not located at a reasonable place in the distribution, this procedure is modified to have a better approximation of the observed distribution. An example of the modeled distributions is shown below on figure 3-22.

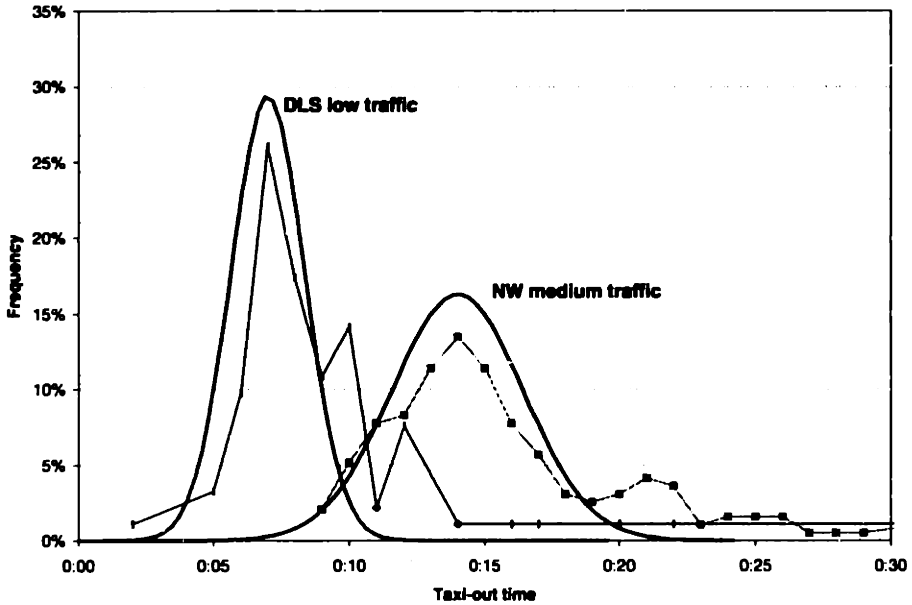

Figure 3-22: Observed and modeled distribution for Delta shuttle under low traffic and Northwest under medium traffic

The values obtained through this process are reproduced on table 3-10.

	AA	CO	DL	DLS	HP	NW	TW	UA	US
First group (low traffic)									
Mean	0:11	0:11	0:11	0:07	0:10	0:15	0:11	0:12	0:09
St. dev.	0:02	0:01	0:01	0:01	0:02	0:03	0:01	0:01	0:01
Second group (medium traffic)									
Mean	0:12	0:12	0:13	0:08	0:10	0:14	0:12	0:13	0:10
St. dev.	0:02	0:02	0:02	0:01	0:02	0:02	0:02	0:02	0:01
Third group (high congestion)									
Mean	0:16	0:15	0:15	0:13	0:17	0:15	0:16	0:15	0:13
St. dev.	0:03	0:02	0:03	0:02	0:04	0:02	0:02	0:01	0:02

Table 3-10: Mean and standard deviation of the Normal distributions approximating the taxi-out times

3.3.5.3 RESULTS

These models are used to estimate the probability that a flight will overtake the one immediately preceding it. This probability is estimated using Riemanian sums. The results are quite good. If all flights with a probability higher than 0.5 are assumed to be predicted as overtaking, this model gives:

	Real L=0		Real L≥1		
Model	**Predicted as such**	**Predicted ≥1**	**Predicted as such**	**Predicted as 0**	**Accurate predictions L**
Dumb	5810	0	0	2506	5810 /8316
Second model	5091	719	1189	1317	6280 /8316
Third model	5300	510	689	1817	5989 /8316
Stochastic m.	5425	385	638	1868	6063/8316

Table 3-11: Comparison of the predictions of the stochastic model and the deterministic models

Using this strict rule, the model performs is less satisfactory than in the second model, but is even more selective: only 6% of the slow flights are predicted as fast.

This model can actually do much more since the probability is a good indicator of the actual likelihood of the swap. This appears clearly on figure 3-23 below.

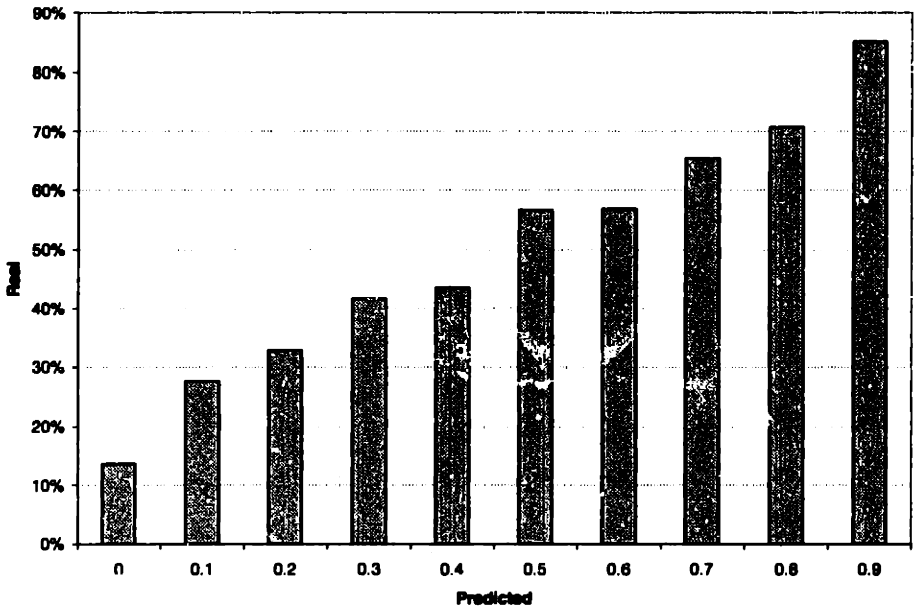

Figure 3-23: Percentage of the flights overtaking as a function of the estimated probability

Considering only the flights with a probability higher than 0.7 allows being even more selective: more than 70% of those flights overtake the previous flights.

3.3.5.4 IMPROVEMENTS

Further improvements to the models would increase the quality of these predictions. For instance, the normal approximation is not very good for some airlines that display two peaks of taxi-out time, or whose gates are spread out. Another development would consist in re-examining the correlation between successive taxi-out distributions.

Once the principle of these models has been outlined and their results validated, the issue comes down to the way this new information must be used in the Control tower. This is discussed in more detail in the next part.

3.4 BUILDING BETTER SEQUENCES

In this section some concepts of sequencing tools that could use the models developed in the previous section are examined. Two issues make this implementation difficult:

(1) Decisions must be taken without knowing what will happen in the next minutes, which means that the runway sequences are constructed considering only what order has already happened.[14]

(2) The only decision that can be taken is to delay an aircraft when it calls ready to push. This simply means that the Clearance Delivery Controller retains its Flight Progress Strip before he/she transfers it to the Ground Controller, who is likely to call the aircraft almost instantly.

3.4.1 Simple control of runway sequences

To show how this model could be used, the impact of a simple control strategy was tested. This consists in adding 2 minutes to all the flights that have a probability greater than 0.7 to overtake the flight that has just pushed back. Using the validation sample and assuming that this change does not affect the probability distributions, the number of flights that are then predicted to overtake their precedent ($P \geq 0.7$) goes down from 453 to 237, i.e. from 5.4% to 2.8%.

Using this simple rule, swaps become significantly less frequent. This strategy does not increase runway system throughput, but it could increase the overall fairness of the process: poorly located airlines would not be systematically overtaken by better located ones.

3.4.2 Avoiding poor runway sequences

The concept for this strategy is described below on figure 3-24. Since the only variable that can be controlled at pushback is the delay inflicted to a flight requesting pushback, this delay will be useful only when the runway system is saturated at the time the flight considered reaches its take-off runway. It is thus necessary to assume that a queue is already formed at the runway threshold. Then, in the case of Logan Airport, since runway saturation is transient, it makes sense to delay a flight E at pushback if it appears likely to overtake a flight D already departed and if the sequence ABCDE is better than the sequence ABCED.

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[14] This problem could be reduced if, as in the SMA program (section 2.3.3.3), the tool had access to airline information on future demand.

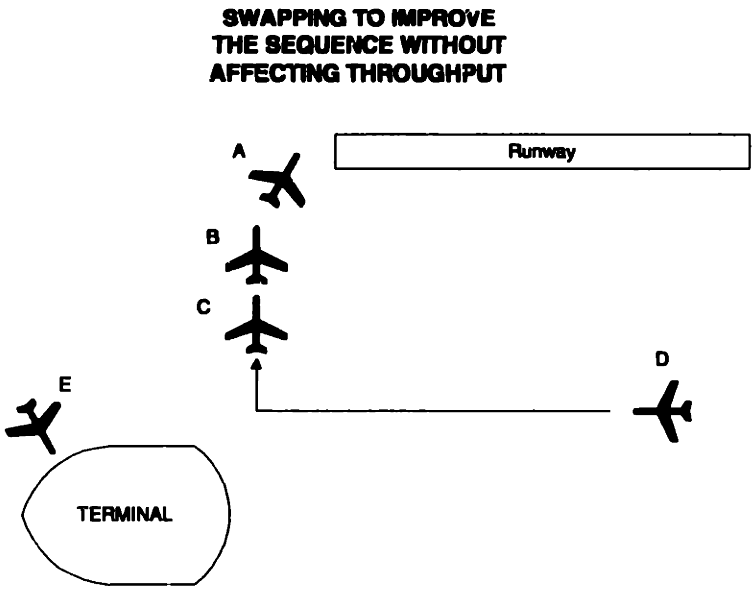

Figure 3-24: A sequence that can be improved using the models

The benefit may be small if the sixth flight in the sequence is of the same type as flight D, but it may be worth it in at least two cases:

- For departure fix or Miles In Trail restrictions, the flights affected are drawn from a small subset, and delaying their arrival at the departure runway by 1 or 2 minutes or flights will often be sufficient to waive these restrictions.[15]
- When the airport is not highly saturated and it is thus unlikely that E is closely followed by a flight of the same type as D.

In any case, in order to avoid indefinitely delaying heavy aircraft, it is necessary to limit the tool-added delay to a maximum value of, for instance, 5 minutes[16].

On the validation sample, while actual decisions to hold aircraft at their gates for traffic management purposes are not accessible, 4.5% of the ORD-bound flights are expected (using the normal distributions) to be within 2 minutes from each other, 7.7% within 5 minutes, and 15.8% within 10 minutes from each other. By applying the models to determine whether an ORD-bound flight departing right after another is likely to reach the runway within less than 2 or 5 minutes, and whether it is likely to overtake some flights, which could put it in a position too close to the first ORD-bound flight, the control tower could easily meet the traffic management restrictions without facing a higher workload at the key control positions.

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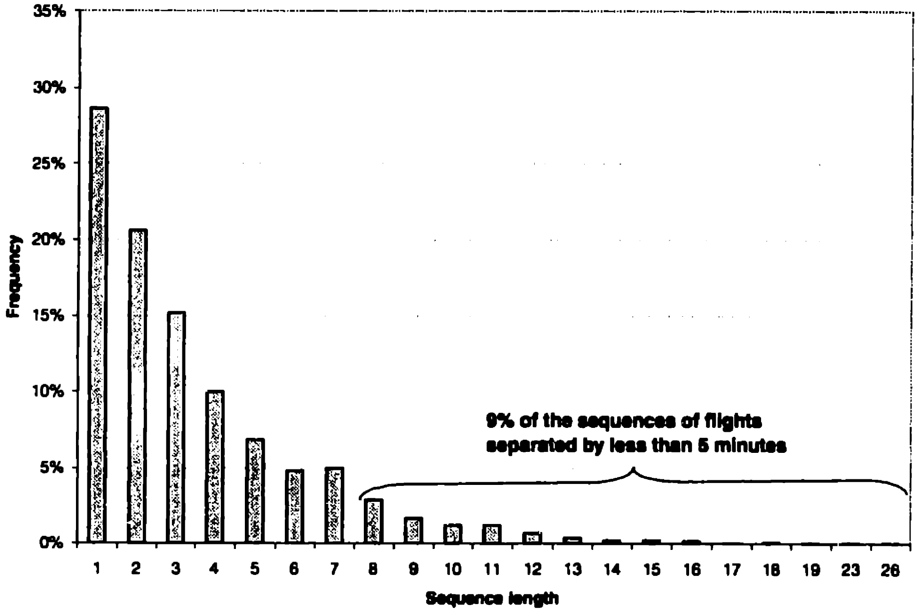
[15] A 20 miles in trail restriction at 500 mph cruise speeds corresponds to 2:20 minutes.

[16] This is a traditional constraint in all sequence optimization programs ("constrained position shifting", etc.).

Positioning heavy flights at the end of the sequences makes also sense since most departures occur by waves of less than 7 or 8 aircraft[17]. This means that delaying heavy jets by a few minutes when they are in the middle of a sequence will often give 1 more minute of runway time[18] without much affecting this operation.



Source: Validation sample, expected takeoff times based on the first stochastic model.

Figure 3-25: Percentages of the expected sequences (separated by less than 5 minutes) by length

The exact benefits from these measures are difficult to estimate because the ASQP database is incomplete. A field test would be necessary to check the actual savings.

3.4.3 Smoothening the runway sequences

3.4.3.1 APPROACH

While the punctual actions suggested in the previous paragraph have a limited scope, the models developed in this research could be used on a constant basis to smoothen the runway sequences.

Starting from the maximum throughput observed at the airport (around 0.4/minute[19], see figure 3-8), the idea is thus to progressively fill slots to smoothen the operations. To maintain the runway system under pressure, it may be necessary to select a smaller slot

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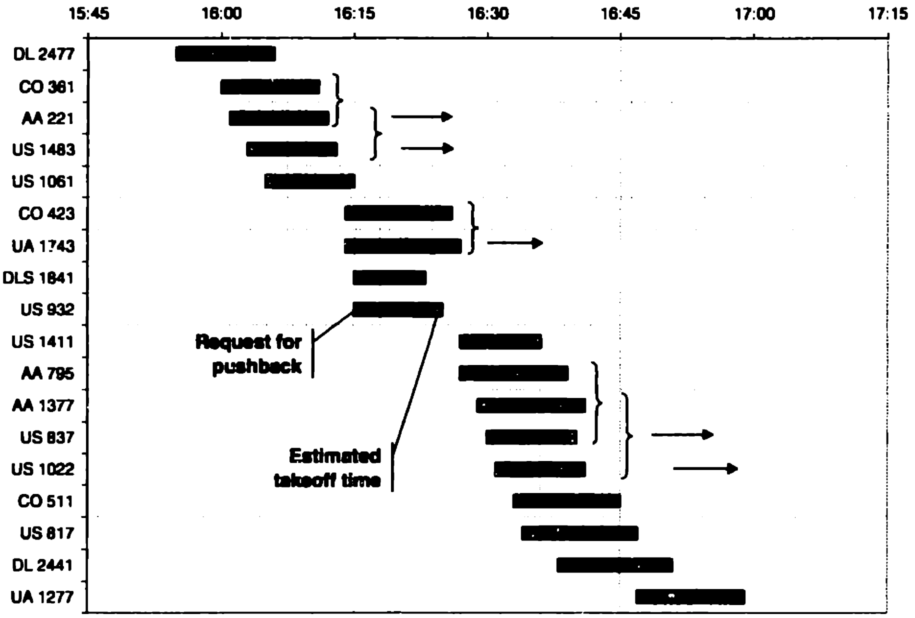
[17] A wave is defined by the fact that the space between two takeoffs is less than 5 minutes.

[18] Since the wake vortex caused by a heavy jet forces the runway to be idle for 2 minutes, versus only 1 minute after a large jet.

[19] Only looking at the ASQP jets.

value, such as 0.6 takeoff/minute, i.e. 100 seconds. The procedure is outlined below on figure 3-26.

This figure shows when pilots requested to pushback, and when these flights were expected to take-off using the average value given by the stochastic model[20]. The tool would delay the flights that are expected to takeoff less than 100 seconds before or after a flight in the departure queue. This happens for instance to flight AA 221 on figure 3-26. This flight would be delayed 40 seconds so as to arrive 100 seconds after CO 361. US 1483 would then be delayed 80 seconds to arrive 100 seconds after AA 221.



Note: The arrows show flights that would be delayed according to the strategy.
Figure 3-26: How to smoothen the runway sequences

Following the analysis of the previous section, these delays will not accumulate for a long time since flights are bunched by small groups. This appears clearly on the example above: the five first flights form a group, the four next, the 8 next, etc. The exact value of the slot can be varied depending on the configuration and the type of aircraft expected to takeoff before the aircraft are released.

This last concept does not sum up to a simple metering of outbound traffic. It considers the times at which the current departures are expected to takeoff and constantly updates these estimates.

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[20] The same reasoning based on the probabilities from this model would be easy to articulate.

3.4.3.2 A SIMPLE EXAMPLE

To show the potential impact of this smoothening mechanism, a simple algorithm was designed to delay selected aircraft to maintain a slot separation S *at the runways* based on the expected takeoff time of the aircraft that have not yet taken off.

The algorithm calculates the correction C(f) to flight f's expected takeoff time T(f) using the following procedure:

1. Consider the last 10 flights that have called ready to push. Identify the window in which f could be located, defined by $T(f_i) + S$ (f_i is the flight that is expected takeoff just before f) and $T(f_j)$ (f_j is the flight that is expected to takeoff right after f).
2. If f_j does not exist, C is the maximum of T(f) and $T(f_i) + S$.
3. If f_j exists, if $T(f_j) - (\max(T(f),T(f_i) + S)) < S$, there is not enough room between them and it is necessary to put f after f_j. Otherwise, it fits and $C(f) = 0$
4. If the latest flight f_k is further than 2 S from f_j, there is no room between them for f, and delaying f by this much (at least 3 S) is excessive. Thus, $C = 0$. Otherwise, it is worth skipping these flights, and $C = T(f_k) - T(f) + C$.

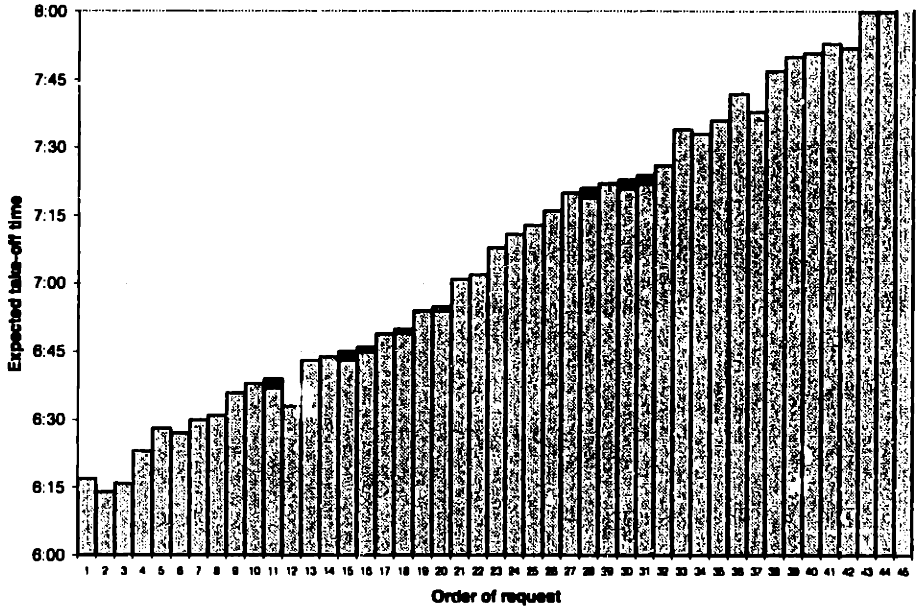

Figure 3-27: Example of the effect of the smoothening algorithm (S= 1 minute)

Figure 3-27 gives examples of the different cases outlined in the algorithm. Most flights are not delayed because they are expected to takeoff more than S after the last flight. Flight No. 12 fits in between flights 8 and 9 and is not delayed either.

While it is difficult to estimate the impact of this algorithm on the runway throughput, it is possible to measure its impact on the predictability of the sequences, and the resulting delays. This study was performed for 3 values of S, and led to the following results.

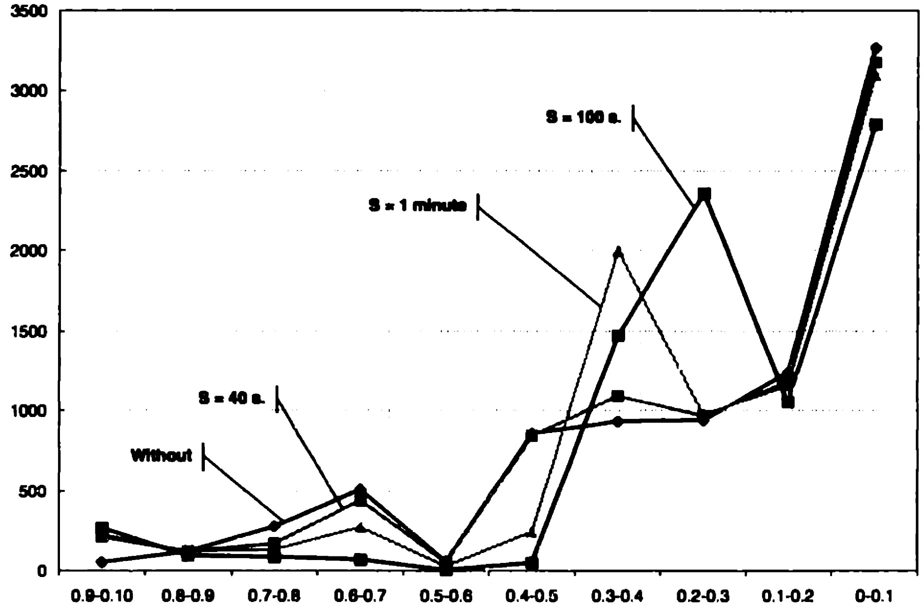

Figure 3-28: Impact of the algorithm on the predictability of operations

Figure 3-28 shows that a 40-second slot does not significantly affect the operations. A 1-minute slot has a much clearer impact on the predictability of the departures:

(1) A few flights are aimed at overtaking some other flights, a fact which increases the number of operations with a P higher than 0.9.

(2) A peak develops around P = 0.3 for 1 minute and P = 0.2 for 1:40 because the flights that are separated by the tool have this type of P (considering standard deviations around 2 to 3 minutes).

The tradeoff is thus the following: it is possible to predict well the sequences of departures by adding selected delays to aircraft before they pushback. This however means delaying *on average* each departure by 12 or 38 seconds.

Slot (seconds)	0	40	60	100
Average delay per operation (seconds)	0	5	12	38
Percentage of flights with P<0.4	77%	77%	87%	92%

Table 3-12: Tradeoff between delay and predictability

This chapter analyzed in detail the departure operations as they occur at Logan Airport. It demonstrated that the transient feature of congestion at this airport gave the opportunity to smoothen the runway sequences to better handle various constraints that apply on departure operations. The departure operations were then modeled using both deterministic and stochastic approaches. While the stochastic approach did not offer better overall predictions, it provided much needed qualitative information to assess these predictions.

The stochastic model showed that it can sustain the development of decision support tools located at the Clearance Delivery position of Logan Airport control tower. These tools will reduce the controllers' workload (or, equivalently, improve the quality of the runway sequences) by proposing limited delays at the transfer of the Flight Progress Strip from the Clearance Delivery controller to the Ground controller. The delays will be based on the likelihood that a better sequence will develop at the runway thresholds.

If the sequences are smoothened as proposed in the third section, an additional benefit can come from the rhythm given to the operations that will make clearer to the downstream controllers the sequence to be developed.

CONCLUSION

At the end of this journey on innovation in Air Traffic Control, various conclusions must be drawn. First, as shown in the first chapter, it would be unjust to state that the ATC system is the "biggest drag on airline productivity"[21]. In the complex mixture of private and public management that shapes the National Airspace System, the private sector is not always the "good guy" who suffers from the deeply entrenched FAA culture that stymies all innovations. Delays have been stabilized in the last few years, traffic management decisions have been fine-tuned and a deeper collaboration has been established on these issues.

Considering the major political hurdles that come with any physical improvement to the large U.S. airports, Decision Support Systems should be strongly supported by policy-makers. For these systems to get implemented, they must deal with controllers' legitimate concerns. The DSEDM project failed because its impact on workload was wrongly estimated. Despite its simplicity, SMA has met a strong need on both sides of airport operations. In general, ATC Innovation must be driven by operational demand and not by technology push.

This new approach was experimentally applied in this thesis on the development of Decision Support Systems in order to provide advice to controllers in helping them handle departure operations. The major concept in this new system can be found in the shift upstream of the decision to build specific sequences. For a controller to be able to take these decisions earlier, it is necessary to develop models of the departure process and estimate the likelihood that a given sequence is achieved. Once this link is modeled, various applications can be envisioned that would either improve the quality of the sequences (i.e. increase the capacity of the airport/overall system) or reduce controllers' workload downstream (i.e. increase safety and control of the take-off sequences).

These initial results support on the one hand the development of such tools while, on the other hand, they call for more basic research on these areas. It must particularly become clear that an important requirement for the success of these tools is that they be

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[21] Aviation Week, July 31, 1995, p. 51.

separated from replacement projects. Of course, replacement systems must be designed openly in order for them to handle new modules as they are developed. Adding more requirements, algorithms and fancy technologies has often led modernization projects to sink either in delays and cost overruns or in too complex requirements. This approach will have to be changed for aviation to benefit from future ATC systems.

APPENDICES

4.1 GLOSSARY

AAS	Advanced Automation System
ACARS	Aeronautical/Radio, Inc. (ARINC) Communications And Reporting System
ACE	Aviation Capacity Enhancement
ADS	Automatic Dependent Surveillance
ARSR	Air Route Surveillance Radar
ARTCC	Air Route Traffic Control Center
ASC	FAA's Office of System Capacity and Requirements
ASD	Aircraft Situation Display (the first phase of the ATMS research and development, and the main component of the ETMS}
ASDE	Airport Surface Detection Equipment (Radar equipment specifically designed to detect all principal features on the surface of an airport)
ASOS	Automated Surface Observing System
ASR	Airport Surveillance Radar
ASTA	Airport Surface Traffic Automation, a component of AAS
ATCSCC	Air Traffic Control System Command Center
ATOMS	Air Traffic Operations Management System
CDM	Collaborative Decision-Making
CFCF	Central Flow Control Facility, synonym of ATCSCC
CNS/ATM	Communication Navigation Surveillance
COMPAS	Computer-Oriented Metering Planing and Advisory System, the German equivalent of CTAS, implemented at Frankfurt since 1991.
CTA	Controlled Times of Arrival
CTAS	Center Tracon Automation System
DSEDM	Departure Sequencing Engineering Development Model
DSR	Display system replacement
EDCT	Estimated Departure Clearance Time
ETMS	Enhanced Traffic Management System
FIDS	Flight Information Display System
FPS	Flight Progress Strips

GDP	Ground Delay Programs
GPRA	1993 Governemment Performance and Results Act
IFR	Instrument Flight Rules
ILS	Instrument Landing Systems
IMC	Instrument Meteorological Conditions
MAR	Managed Arrival Reservoirs
MLS	Microwave Landing Systems
NAS	U.S. National Airspace System
PDC	Pre-Departure Clearance
PRM	Precision Runway Monitor
RVR	Runway Visual Range
SID	Standard Instrument Departure route
SMA	Surface Movement Advisor
TAP	Terminal Area Productivity
TARMAC	Taxi And Ramp Management And Control
TCAS	Traffic Alert and Collision Avoidance System
TRACON	Terminal Radar Approach Control facility
VAS	Wake Vortex Advisory System
VFR	Visual Fligth Rules
VMC	Visual Meteorological Conditions
VOR	VHF Omnidirectional Range stations
WVAS	Wake Vortex Avoidance System

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4.3 DAILY WEATHER DATA FORMAT

Field	Position	Type	Description
STN	1-6	Int.	Station number (WMO/DATSAV2 number) for the location.
YEAR	9-12	Int.	The year.
MODA	13-16	Int.	The month and day.
TEMP	19-24	Real	Mean temperature for the day in degrees Fahrenheit to tenths. Missing = 9999.9 (Celsius to tenths for metric version.)
Count	26-27	Int.	Number of observations used in calculating mean temperature.
DEWP	30-35	Real	Mean dew point for the day in degrees Fahrenheit to tenths. Missing = 9999.9 (Celsius to tenths for metric version.)
Count	37-38	Int.	Number of observations used in calculating mean dew point.
SLP	41-46	Real	Mean sea level pressure for the day in millibars to tenths. Missing = 9999.9
Count	48-49	Int.	Number of observations used in calculating mean sea level pressure.
STP	52-57	Real	Mean station pressure for the day in millibars to tenths. Missing = 9999.9
Count	59-60	Int.	Number of observations used in calculating mean station pressure.
VISIB	63-67	Real	Mean visibility for the day in miles to tenths. Missing = 999.9
Count	69-70	Int.	Number of observations used in calculating mean visibility.
WDSP	73-77	Real	Mean wind speed for the day in knots to tenths. Missing = 999.9
Count	79-80	Int.	Number of observations used in calculating mean wind speed.
MXSPD	83-87	Real	Maximum sustained wind speed reported for the day in knots to tenths. Missing = 999.9
GUST	90-94	Real	Maximum wind gust reported for the day in knots to tenths. Missing = 999.9
MAX	97-102	Real	Maximum temperature reported during the day in Fahrenheit to tenths--time of max temp report varies by country and region, so this will sometimes not be the max for the calendar day. Missing = 9999.9
Flag	103-103	Char	Blank indicates max temp was taken from the explicit max temp report and not from the 'hourly' data. * indicates max temp was derived from the hourly data (i.e., highest hourly or synoptic-reported temperature).
MIN	105-110	Real	Minimum temperature reported during the day in Fahrenheit to tenths--time of min temp report varies by country and region, so this will sometimes not be the min for the calendar day. Missing = 9999.9
Flag	111-111	Char	Blank indicates min temp was taken from the explicit min temp report and not from the 'hourly' data. * indicates min temp was derived from the hourly data (i.e., lowest hourly or synoptic-reported temperature).
PRCP	113-117	Real	Total precipitation (rain and/or melted snow) reported during the day in inches and hundredths; will usually not end with the midnight observation--i.e., may include latter part of previous day. .00 indicates no measurable precipitation (includes a trace) Note: Many stations do not report '0' on days with no precipitation--therefore, '99.99' will often appear on these days. Also, for example, a station may only report a 6-hour amount for the period during which rain fell. See Flag field for source of data.
Flag	118-118	Char	A = 1 report of 6-hour precipitation amount. B = Summation of 2 reports of 6-hour precipitation amount. C = Summation of 3 reports of 6-hour precipitation amount. D = Summation of 4 reports of 6-hour precipitation amount. E = 1 report of 12-hour precipitation amount. F = Summation of 2 reports of 12-hour precipitation amount.

			G = 1 report of 24-hour precipitation amount.
SNDP	120-124	Real	Snow depth in inches to tenths--last report for the day if reported more than once. Missing = 999.9 Note: Most stations do not report '0' on days with no snow on the ground--therefore, '999.9' will often appear on these days.
FRSHTT	127-132	Int.	Indicators (1 = yes, 0 = no/not reported) for the occurrence during the day of: Fog ('F' - 1st digit). Rain or Drizzle ('R' - 2nd digit). Snow or Ice Pellets ('S' - 3rd digit). Hail ('H' - 4th digit). Thunder ('T' - 5th digit). Tornado or Funnel Cloud ('T' - 6th digit).

Table 4-1: Daily weather data format

4.4 VALIDATION OF THE ASQP DATABASE

4.4.1 ASQP versus OAG

How representative are ASQP data of the behavior of the entire airport? To answer this question, since it is not possible to have access to the entire exact operations that happened at the airport on a given day, we examined the difference between the Official Airline Guide schedule and the schedule of the ASQP airlines on a single day. This analysis gives the following results:

Airline	Published departures	Reported in the ASQP	Not reported because			
			Regional	International	Shuttle	Unexplained
AA	55	41	9	4	0	1
CO	32	32	0	0	0	0
DL	181	61	110	10	0	0
HP	6	6	0	0	0	0
NW	22	21	0	1	0	0
TW	19	8	11	0	0	0
UA	70	39	31	0	0	0
US	197	79	101	1	17	-1
Other airlines	101					
Total	683	287	262	16	17	0

Source: OAG and ASQP systems for July 9, 1997. Notes: Delta shuttles are included in the ASQP while US Air Shuttle belong to a separate entity and are thus not reported.

Table 4-2: Differences between OAG and ASQP on a single day

By using the OAG schedule of these 287 ASQP reported departures and rescaling it, we would obtain the schedule of departures shown on figure 4-1.

This figure shows that the schedules of these two groups are similar, but that we must be aware of the following differences:

(1) ASQP carriers have a strong scheduled pushback in the early morning (6:00 to 8:00)

(2) They represent a smaller share of the operations at lunch time (11:00 to 14:00)

(3) This advance is compensated at night: after 21:00, ASQP carriers do usually not handle scheduled departures. Out of the 19 departures scheduled after 21:00, only 2 are reported in the ASQP, while there are 12 regional departures, one US Air shuttle and 4 international flights.

These results are not surprising since airline provide larger aircraft for the naturally stronger demand early in the morning.

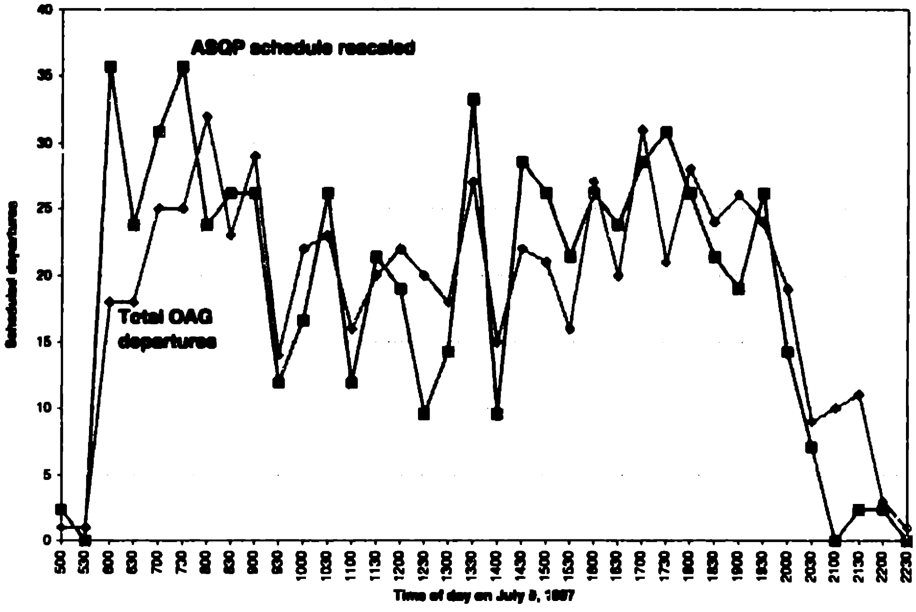

Figure 4-1: Difference in scheduling between ASQP airlines and the entire OAG

A further analysis in terms of preference for a specific moment of each hours shows that ASQP departures happen more often at the round minutes (00, 30 and 45), and less at uncommon minutes (25, 35, 50, 55). This is not surprising considering airlines' scheduling practice that assume that passengers prefer to depart at round hours, and that it is thus better to provide larger aircraft (the jets reported in the ASQP and not regional aircraft) at these moments. The fact that passengers usually ask their travel agents for a flight at round hours increases this phenomenon.

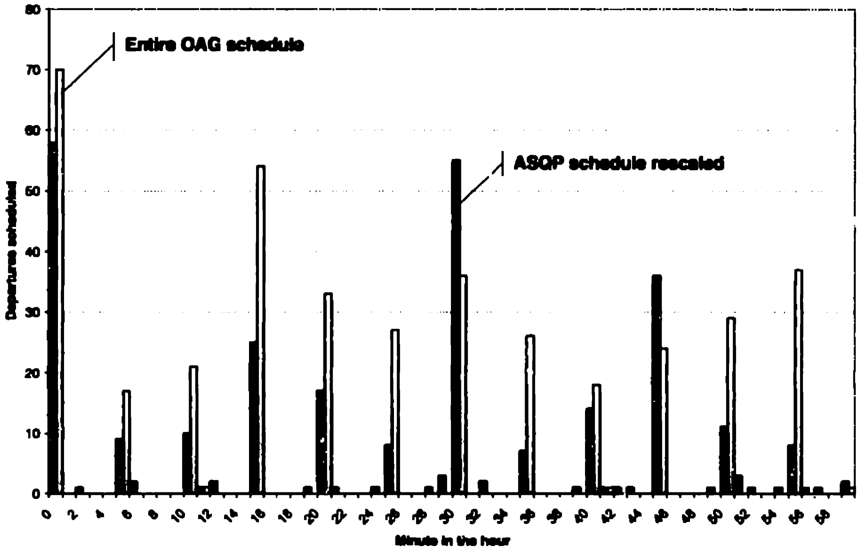

Figure 4-2: Difference in scheduling between the ASQP database and the OAG: within each hour

4.4.2 ASQP versus actual observations

Validation was performed at Logan airport during two short periods in February and March 1998. It requires following aircraft as they pushback and takeoff (land and park) and note the time of these events and the tail number of the aircraft, which is difficult even from the control tower[1]. This validation gives the following results.

Airline	Tail No.	Time 1st event	Time 2nd event	Equival. in ASQP	1st event	2nd event	Difference 1st event	Difference 2nd event
AA	N301AA	16:22	16:38		16:26	16:41	0:00	0:01
DL	N414DA	16:24	16:30		16:29	16:35	0:01	0:01
CO	N13891	16:26	16:37		16:30	16:40	0:00	0:01
DL		16:33						
DL	N613DL	16:40	16:46		16:44	16:54	0:00	0:04
AA	N669AA	16:44	16:50					
AA	N77080	16:45	16:55					
AA	N307AA	16:47	16:55		16:48	16:58	0:03	0:01
UA	N562UA		16:39			16:43		0:00
UA	N354UA		16:58			17:01		0:01
Departures								
AA	N70054	16:34						
DL	N407DA	16:38			16:45		0:03	
UA	N410UA	16:39			16:44		0:01	
DL	N118DL	17:00	17:11		17:03	17:14	0:01	0:01
NW	N275US		17:10					

Note: The differences assume an offset of 3 minutes between the two clocks. The gray cells correspond to absolute differences larger than 1 minute.

Table 4-3: Differences between ASQP data and observations, first day

Airline	Tail No.	Time 1st event	Time 2nd event	Equival. in ASQP	1st event	2nd event	Difference 1st event	Difference 2nd event
DL	N481DA	2:22			14:29	14:32	0:04	
US	N957VJ	2:32		??	14:36	14:45		
DL	N312DL	2:36	2:40		14:39	14:44	0:00	0:01
US	N223US	2:38			14:42	14:48	0:01	
DL	N606DL	2:40			14:43	14:49	0:00	
DL	N956DL	2:44	2:51		14:48	14:54	0:01	0:00
AA	N549AA	2:48	2:56		14:51	15:00	0:00	0:01
UA	N441UA	2:50	2:57		14:53	15:00	0:00	0:00
AA	N14DIG	2:52	2:59	similar	14:55	15:02	0:00	0:00
DL	N308DL	2:59	3:05		15:02	15:11	0:00	0:03
CO	N14889	3:05	3:15		15:08	15:20	0:00	0:02
US	N244US	3:08	?		15:12	15:21	0:01	
DL	N122DL		2:15		14:09	14:19		0:01
AA	N070AA		2:17		14:14	14:20		0:00
US	N349US		2:18		14:11	14:25		0:04
UA	N7273U		2:18		14:13	14:22		0:01
US	N973VJ		2:21		14:18	14:27		0:03

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[1] It is impossible to see all the gates of the airport from any single point, and thus impossible to record pushback times for all airlines. Arrivals are easier to track since they can be monitored before they land.

Departures								
UA	N309UA	2:21	2:30		14:23	14:33	0:01	0:00
AA	N576AA	2:24	2:35		14:25	14:38	0:02	0:00
DL	N321DL	2:27	2:35		14:25	14:42	0:05	0:04
DL	N417DA	2:28	2:38		14:30	14:40	0:01	0:01
UA	N576UA	2:47	2:58		14:50	15:01	0:00	0:00
UA	N7273U	2:49	3:02		14:51	15:06	0:01	0:01
AA	N669AA	2:57	3:07	N5CTAA	14:59	15:11	0:01	0:01
AA	N471AA	3:09	3:17		15:11	15:20	0:01	0:00
DL	N920DE	3:09	3:19		15:10	15:22	0:02	0:00
US			2:31	N444US	14:18	14:28		0:06
US	N445US?		2:36	N922VJ	14:26	14:34		0:05
CO	N77827		2:44		14:33	14:47		0:00
US			3:03	N282AU	14:57	15:07		0:01
CO	N35636		3:09	??	14:59	15:12		0:00

Note: The differences assume an offset of 3 minutes between the two clocks. The gray cells correspond to absolute differences larger than 1 minute.

Table 4-4: Differences between ASQP data and observations, first day

Two conclusions can be drawn from these small samples:

(1) ASQP data are in general accurate, and particularly for wheels off and landing times

(2) Nevertheless, more discrepancies can be found at the gates because the fact that the visual observation that an aircraft starts or stops does not always correspond exactly to the brake release/pull.

In consequence, the models developed in this thesis conserve their validity, but the actual taxi-out averages may be lower since some of the pushback probably occurred later than recorded. This variation may explain some of the values observed on the right hand tail of the taxi-out distributions.

4.5 AIRLINE DATA: MAIN CAUSES OF DELAYS

4.5.1 Out to Off delay reports

This database is presented in section 2.2.2.2, p. 65. Besides time in the departure queues that represents the bulk of the delays, two causes are unfrequent but have a large impact on airline A operations.

Item	Number	Total minutes	Average delay	% of reported flights	% of delays
Other Flights landing or departing	2784	22419	8	65%	61%
ATC Hold for departure control	123	2875	23	3%	8%
Awaiting ATC Enroute Clearance	86	2768	32	2%	8%
Ramp Delays during pushback (equipment/congestion)	355	2148	6	8%	6%
Field Traffic	405	2091	5	9%	6%
Awaiting radio closeout Info	144	1147	8	3%	3%
Runway Change	97	1010	10	2%	3%
Taxi Congestion	190	948	5	4%	3%
Airplane systems operational check, cabin check, etc.	60	539	9	1%	1%
Awaiting takeoff weather minimums	10	376	38	0%	1%
Re-calculation of Takeoff performance data	46	342	7	1%	1%

Table 4-5: Major causes of delays between Out and Off, as reported by airline A pilots

4.5.2 Delays prior to pushback

This database is presented in section 2.2.2.2 p. 66. The same phenomenon occurs before pushback: beside flow control, two causes are infrequent but induce large delays (Mechanical reliability and legality of cockpit crews) while, and the other causes are frequent but induce small delays.

Item	Number	Total minutes	Average delay	% of reported flights	% of delays	Division
Flow Control	273	13718	50	5%	19%	Weather/ATC
Mechanical Reliability	218	8227	38	4%	11%	Maintenance
Legality - Cockpit crew	104	5807	56	2%	8%	Crew
Local Tower ATC	1741	5580	3	30%	8%	Weather/ATC
Weather	98	3749	38	2%	5%	Weather/ATC
Miscellaneous other	660	3178	5	11%	4%	Miscellaneous
Slow boarding/closeout	249	1852	7	4%	3%	Customer service
Resources	69	1819	26	1%	3%	Maintenance
Bag Loading	286	1752	6	5%	2%	Ramp service
Material and Parts	26	1741	67	0%	2%	Maintenance
Consolidation	170	1643	10	3%	2%	Customer service
Snow/Ice removal	93	1547	17	2%	2%	Ramp service
Facilities	110	1526	14	2%	2%	Other Station Operations
Gate checked baggage	309	1451	5	5%	2%	Customer service

Table 4-6: Major causes of delays before pushback, as reported by airline B pilots