Queuing Dynamics and Control of Departure Operations at Boston Logan Airport

By

Husni Rifat Idris

S.B. and S.M. in Mechanical Engineering
Massachusetts Institute of Technology, 1989 and 1992

PH.D. in Human Factors and Automation
Massachusetts Institute of Technology, 2001

Submitted to the Sloan School of Management
in Partial Fulfillment of the Requirement for the Degree of
Master’s of Science in Operations Research

at the

Massachusetts Institute of Technology

February 2001

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Abstract

The Departure Planner (DP) is a concept for a decision-aiding tool that is aimed at improving the performance of departure operations at major congested airports. In order to support the development of DP tools and other improved methods for departure operations, this thesis is an effort to gain a deep understanding of the underlying dynamics of the departure process based on field observations and data analysis conducted at Boston Logan International Airport. It was observed that the departure process is a complex interactive queuing system and a highly controlled system as the air traffic controllers manage the traffic. Based on these observations, a core departure process abstraction was posed which consists of a queuing element that represents the delays and a control element that represents the air traffic controller actions. Namely, the abstraction represents the control element by blocking the flow of aircraft in order to maintain the safe operation of the airport resources according to the ATC rules and procedures and to regulate the outbound flow to constrained downstream resources. Based on this physical abstraction, an analytical queuing framework was posed and used to analyze the departure process dynamics under different scenarios: the overall departure process between pushback and takeoff, departure sub-processes between controller/pilot communication events and under the effect of downstream restrictions. Passing was used as a manifestation of the control behavior, where passing results mainly from sequencing of aircraft and their suspension under special circumstances such as downstream restrictions. Insights about the departure process queuing dynamics and control behavior are discussed. In particular it was observed that at Logan airport there is a high level of uncertainty and a limited level of sequencing control, hindering the ability of the air traffic controllers to manage the traffic efficiently and in compliance with restrictions.

Thesis Supervisor: Amedeo R. Odoni
Title: Professor, Department of Aeronautics and Astronautics, Department of Civil and Environmental Engineering and Operations Research Center
Acknowledgements

To my advisor, Professor Amedeo Odoni, thank you for your guidance and support throughout my research.

To Professors Amedeo Odoni, R. John Hansman, Robert Simpson, Thomas Sheridan and Dennis Mathaisel, thank you for inspiring my interest in human factors, operations research and air traffic control, and for your guidance and advice throughout my research. Also thanks to Professors John-Paul Clarke and Eric Feron for your feedback throughout this project.

To all the Control Tower personnel at Logan Airport, who were instrumental to this research, thank you for providing the opportunity to conduct field observations, for providing knowledge and data and for supporting research efforts in this thesis and in general. Special thanks to the Control Tower chief Mr. Joe Davies, to the Control Tower managers Mr. Ronald Crossman and Mr. Donald Crossman, to the Control Tower supervisor Mr. Michael Hilliard and to the Control Tower traffic management coordinator Mr. Michael Lahey.

Thanks to my colleagues who helped in conducting field observations and collecting data at the Logan Control Tower.

Special thanks to NASA Ames for supporting this research. Special thanks to Dr. Leonard Tobias and Dr. Steve Atkins. Special thanks also to the Joint University Program, under the support of the FAA and NASA Ames, for supporting my research for many years and for providing an excellent environment for continued progress through the quarterly meetings. Thanks to all my friends that I met through this program. Also thanks to all my friends and colleagues in the International Center for Air Transportation at MIT.

To all my friends, thanks for your caring, support and encouragement.

To my brother Khaled, thank you for being a wonderful friend and roommate and for supporting and helping whenever possible.

To my mother and my late father, thank you for your love and support, which I can never repay. I love you and dedicate this work to you.

Most importantly, thanks to God for giving me the health and the will to complete this work and I hope that it will contribute to a better life for all.
To my mother Souha Al-Atassi and

to the memory of my father Rifat Idris
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Chapter 1

Introduction

While demand for air travel has increased dramatically, and is expected to keep increasing at a high rate\(^1\), the U.S. National Airspace System (NAS) is reaching capacity limitations. As a result, major airports and airspace sectors are experiencing high congestion and costly delays. The Federal Aviation Administration (FAA) estimated the total delay costs in 1994 at about 9.5 billion dollars (Delcaire). Most importantly, as the number of aircraft in a given airspace region increases, the workload of the air traffic controllers increases, and maintaining safety – which is the main task of the Air Traffic Control system – becomes a critical concern.

In order to reduce the congestion and delays in the NAS a number of approaches can be pursued. On the capacity side, plans to increase the capacity of the NAS by adding new airports and new runways are usually expensive, long term projects and often face considerable political opposition from the communities that are affected by environmental impacts such as noise. On the demand side, attempts can be made to alter the airlines scheduling behavior through peak pricing policies (Barrett). Some efforts have focused on improving the efficiency of the system and reducing the delays through technological advances. One such type of effort is the introduction of decision support systems that may assist air traffic controllers in managing traffic. The work in this thesis is motivated by attempts to improve the performance of the airport system, and specifically the departure operations, through the introduction of such decision aiding systems.

\(^1\) "The world's air travelers are projected to double in number over the next 20 years, to more than 2 billion." From the Washington Post, December 12, 1997 reported in Delcaire [1998].
1.1 Motivation

Because of the higher cost and more critical safety concerns associated with airborne delays, most of the reported delays in the NAS are incurred on the ground of the airports by departure aircraft prior to their takeoff. The Departure Planner (DP) is a concept for a decision aiding system that would assist air traffic controllers in managing the departure operations at major congested airports (Idris, Anagnostakis). In order to support the design and development of DP tools and similar improved methods for departure operations, a clear understanding of the departure process dynamics is required. In this thesis, an attempt is made to gain such an understanding by modeling the departure process as a queuing system, controlled by the air traffic controllers.

1.2 Problem statement

In particular, the problem addressed in this thesis is the modeling and analysis of the tactical behavior of the departure process, where the tactical behavior refers to the movement of aircraft on the airport surface, under strict control by the air traffic controllers. In order to gain in-depth understanding of the factors that impede the movement and progress of an aircraft in the departure process, a high level of detail in the analysis is motivated. Therefore, a microscopic approach is adopted, whereby the dynamics of every single aircraft, as it progresses through the departure process, are analyzed. This is achieved by analyzing the time that an aircraft spends in the departure process, accounting for the main constraining factors that contribute to this time and cause delays. These factors include natural factors that are related to the flow demand of aircraft relative to the flow capacity of the airport resources, and procedural factors that are
caused by the Air Traffic Control system. On the other hand, while a detailed analysis is desired, the level of detail is limited by the observability that can be achieved by the available data.

1.3 Literature review

A number of approaches have been followed in the modeling and analysis of the departure process and the airport system in general, which may be classified in terms of their level of detail. At one end, an airport system is modeled in a most simplified representation, as a node in the NAS network of airports and air routes. The airport node acts as a sink that receives inbound flow from the network and as a source that delivers outbound flow to the network, and is therefore, represented with a set of arrival and departure rates. For example, Gilbo developed airport capacity models by estimating the arrival and departure flow rate capacities of an airport system and the relation between them, based on the Enhanced Traffic Management System (ETMS) data of airport actual throughputs. Recently, these approaches have been extended to suggest the use of the developed capacity models in a Collaborative Decision-Making (CDM) environment to allocate the airport capacity efficiently between airlines (e.g. Gilbo [2000] and Hall [1999]). Other models that represent the airport system as a node in the NAS network include the Approximate Network Delays (A.N.D.) (Odoni, Malone). Using such models the propagation of delays at the scale of the NAS is studied but details of individual airport operations are not captured.

At the other end, there are simulations of airport systems that attempt to model the airport behavior in great detail. Such details include the aircraft motion, the airport network of gates, ramps, taxiway links and runway strips, as well as the air traffic controllers' behavior in some
cases. Examples of such simulations include TAAM\textsuperscript{2} (Total Airspace and Airport Modeler) and SIMMOD. For example, Polak used a TAAM simulation to determine the bottlenecks in an airport system (Schiphol Airport) and evaluate solution strategies.

Between the two extremes, some approaches developed classical queuing models to represent and analyze the airport departure process with a moderate level of detail. Using simple queuing system representations, these approaches built statistical models of departure rate capacity and taxi out delays. Such models were used to analyze the system dynamics and to test estimation and control concepts (e.g. Andretta, Herbert, Shumsky, Pujet, Delcaire, Andersson, Carr). Andersson et al extended their predictive models of the departure process to arrivals and gate operations.

1.4 Approach and contribution of the thesis

The approach followed in this thesis is a queuing approach that differs from prior approaches in a number of ways in order to analyze the dynamics at the desired level of detail, which captures delay causal factors and tactical control behavior:

- The approach is microscopic in the sense that the queuing dynamics are analyzed from the point of view of a particular aircraft, as opposed to analysis of the dynamics of the aircraft queuing system at a particular time.

\textsuperscript{2} TAAM is "a large scale fast-time simulation model, designed to simulate very realistically all possible aspects of the air traffic, on the ground as well as in the air." (Polak).
• In this microscopic approach the sequencing behavior is identified where an aircraft may leave the departure process in an order that is different from the order of its entry into the process. The effect of sequencing on the time that an aircraft spends in the process is analyzed.

• The approach also identifies the procedural control behavior, which is attributed to the role of the air traffic controllers in managing the traffic flow and controlling the aircraft movement. Such control behavior manifests mainly in sequencing and in time control of aircraft under specific conditions.

1.5 Thesis outline

In Chapter 2, the departure process is described and is abstracted, in a physical representation, as a controlled queuing system, where queues represent the delays incurred by aircraft and control mechanisms represent the controllers' actions in managing the flow. In chapter 3, this controlled queuing system is used as a lumped element representation of the departure process or any sub-process of it—defined between specific events. An analytical framework corresponding to the lumped element representation is posed, with an explicit representation of the queuing elements and the procedural control elements. This framework is then used to analyze the queuing dynamics and the control behavior under different scenarios: the overall departure process between pushback and takeoff in Chapter 4, the communication-based departure sub-processes in Chapter 5, and under downstream restrictions in Chapter 6.

Following is a list of the symbols used in the thesis.
List of symbols

\( t_{\text{entry}} \) Time of entry into the system or process

\( t_{\text{exit}} \) Time of exit from the system or process

\( D \) Time in the system = \( t_{\text{exit}} - t_{\text{entry}} \) (taxi out time for the overall departure process analysis)

\( D_r \) Desired time in the system

\( N \) Queue size experienced by a particular aircraft

\( N_{\text{FCFS}} \) FCFS queue component size experienced by a particular aircraft

\( N_p \) Number of aircraft that passed a particular aircraft

\( N^p \) Number of aircraft that were passed by a particular aircraft

\( N_0 \) Number of aircraft in the system (taxiing) at pushback time of a particular aircraft

\( ES \) Effective service time (free-flow time)

\( S \) Actual service time

\( S_p \) Procedural service time (interruption of actual service)

\( EW \) Effective waiting time

\( W_{\text{FCFS}} \) FCFS waiting time due to the FCFS queue component \( N_{\text{FCFS}} \)

\( W_p \) Procedural waiting time due to the passing queue component \( N_p \)

Symbol for gates

Symbol for the ramp

Symbol for the taxiways

Symbol for the runways
Chapter 2

Overview of the departure process: A controlled queuing system

Based on observations of the airport system, conducted at Boston Logan International Airport and described in (Idris), it was observed that the departure process forms a complex interactive queuing system, where aircraft form queues at different locations in the airport system because of flow constraints. It was also observed that the departure process is a highly controlled process, where the air traffic controllers dictate the aircraft movement in the areas under their control in order to maintain safe operations and to regulate the flow to downstream locations. Therefore, based on these main observations, the departure process is abstracted at the tactical level as a queuing system with controlled blocking, as described in this chapter.

2.1 Operation of a single airport resource

The air traffic controllers control the operation of an airport resource, such as a runway, a taxiway segment, a ramp or a gate, through communication with the pilots. In general, the pilot calls the air traffic controller in charge, stating that the aircraft is ready to use an airport resource. The air traffic controller then gives the approval, as appropriate, by delivering a control instruction\(^3\). The basic control instruction is the ATC clearance, which is the instruction issued

\(^3\) In many instances, an air traffic controller who is monitoring the progress of the aircraft under his or her control may realize that the aircraft is ready for the next phase. The controller then may proceed to deliver the control instruction without any prompting from the aircraft.
by the air traffic controller to an aircraft to perform an operation using any airport resource that is under his or her control. For example, a Local controller in charge of a departure runway clears aircraft for takeoff by delivering the basis instruction "clear for takeoff"; and a Ground controller delivers the clearance "clear for taxi" to aircraft demanding use of any taxiway segment of the taxiway system in his or her area of responsibility. Opposite the clearance instruction is the instruction to **hold**, where the hold instruction is assumed unless the clearance is delivered explicitly. Figure 2.1 shows a physical abstraction of the operation of a generic airport resource as a controlled queuing system. Since the clearance is required to use every airport controlled resource it is depicted in the Figure as a switch that is in a closed default state unless the clearance is delivered by the air traffic controller in charge of the resource.

![Diagram of airport resource operation](image)

**Figure 2.1**: The operation of a generic airport controlled resource

As shown in Figure 2.1, in addition to the basic clearance, the air traffic controller may control the aircraft through **sequencing** (when there are multiple queues demanding service of the resource), through **suspending** (when there is a dedicated suspension area associated with a
queue) and through **routing** (when there are multiple downstream queues or resources that the aircraft may join). For example, the control instruction may include a route (such as a taxi route assignment to the designated runway) or a sequence (such as sequencing aircraft at merging points on the taxiways or sequencing aircraft in the takeoff queue). These instructions may be combined; for example, a controller may instruct aircraft A: “Give way to aircraft B, then clear for taxi to runway 22R, via Alpha, Kilo and November.” Such an instruction includes a taxi route, a runway assignment, and a sequence behind aircraft B, as well as the clearance to use the taxiway resources. In cases of aircraft-specific circumstances that require absorbing delays, aircraft may be suspended either on the gate or in designated delay absorbing areas. If the next operation is under the control of another air traffic controller, a **handoff** is required. The air traffic controller in this case hands off the aircraft control to the next controller\(^4\) and instructs the aircraft to change the communication channel frequency. The next air traffic controller then delivers the control instruction.

Therefore, an air traffic controller controls an airport resource through the basic control mechanism—the clearance—and the complementary control mechanisms such as sequencing, suspending and routing, when possible. Aircraft form queues in front of the airport resource as shown in Figure 2.1, due to the resource capacity limitation. The capacity limitation of the resource is caused by the finite time that the aircraft takes to operate on the resource (such as the time to taxi on a taxiway segment or takeoff on a runway) as well as the implementation of ATC procedures through the different control mechanisms, which often results in interruption of operation. For example, the air traffic controller in charge of a runway has to insure the safe

\(^4\) Usually using a flight progress strip, which is a paper strip that identifies each aircraft and is used to manually hand off aircraft control between successive controllers in the Control Tower.
operation of the runway by maintaining the runway and wake vortex separation requirements between takeoffs, landings and runway crossings. This is achieved by holding the clearance from aircraft demanding the use of the runway until such separations are satisfied.

### 2.2 Interaction between airport resources

Figure 2.2 shows the physical abstraction of the airport resource operation (of Figure 2.1) in addition to the interaction with other resources within the departure process and in the overall NAS.

![Diagram of airport resource interaction](image)

**Figure 2.2: The basic elements of the departure process**
Figure 2.1 shows the different possibilities of interaction and feedback: Feedback may be through a single air traffic controller in charge of multiple resources and queuing systems. For example, a Local controller might be in charge of multiple runways and a Ground controller is usually in charge of multiple taxiways. Feedback may also be through cooperation between adjacent air traffic controllers. For example, the Gate controller has to regulate the flow of departure aircraft given the state of the traffic on the airport surface on the taxiways and runways (in some cases at the request of the adjacent Ground controller). Finally, in the case of downstream resources outside the airport system (such as exit fixes, airspace sectors and destination airports), feedback is established through a flow management process, which results in downstream restrictions that are imposed on the outbound flow. For example, as indicated in Figure 2.1, an Airport Acceptance Rate (AAR) and a sector’s Operationally Acceptable Level of Traffic (OALT) may be used as indications of the downstream capacity limitations, such that appropriate flow restrictions are imposed on the outbound flow to these locations.

There are three main types of downstream flow restrictions (See FAA, Course 50115):

*Takeoff time window*

Two flow management programs impose a restriction on a departure aircraft in the form of a requested takeoff time within a specific time window, the Expected Departure Clearance Time

5 Feedback between controllers may be direct if they are adjacent or through the Supervisor and Traffic Management Coordinator of the Tower. Some control facilities such as Newark also employ a Tower Coordinator position to enhance the interaction.

6 The Airport Acceptance Rate (AAR) is the number of inbound aircraft that an airport can accept in an hour and it depends on the available runways, weather conditions and other factors.

7 A sector’s Operationally Acceptable Level of Traffic (OALT) is the number of aircraft that the sector can handle (or accept) in an hour. It depends on a number of factors including weather and workload.
(EDCT) and the Departure Sequencing Program (DSP). EDCT is a Ground Delay Program (GDP), in which the ATCSCC\textsuperscript{8} selects certain flights (heading to a capacity limited destination airport) and assigns an Expected Departure Clearance Time (EDCT) to each flight individually, with a 15-minute time window. The Departure Sequencing Program (DSP) is a program designed to assist in achieving a specified interval for departures over a common point (such as a fix). In order to achieve the specified interval over the common point a DSP wheels-off time is assigned by the ARTCC\textsuperscript{9} to each affected aircraft such that it arrives at the common point in a given time slot. The DSP wheels-off time has to be met with a maximum 3-minute delay. If the time window is missed, the Tower has to call the ATCSCC (in the case of an EDCT) or the ARTCC (in the case of a DSP) for another time assignment.

\textit{Takeoff spacing}

Miles-in-Trail and Minutes-in-Trail restrictions are imposed in terms of spacing between departure aircraft. Miles-In-Trail (MIT) is a specified distance between aircraft, normally, in the same stratum associated with the same destination or route of flight. Minutes-In-Trail (MINIT) is a specified interval between aircraft expressed in time.

\textit{Time delay}

Through the Ground Delay Program, GDP, a time delay for a specific duration may be imposed by the ATCSCC on departure aircraft heading to a constrained destination (for example,\textsuperscript{10})

\textsuperscript{8} The ATCSCC is the Air Traffic Control System Command Center, which is in charge of flow management throughout the NAS.

\textsuperscript{9} The ARTCC is the Air Route Traffic Control Center, which is in charge of the en-route traffic in an airspace sector in the NAS. The airspace sector may include a number of airports.
departures to ORD, 12:00 to 12:59, 15 minute delay). While the GDP is used for long term demand regulation, for short-term effects the ATCSCC uses the Ground Stop (GS), which stops all departures to an affected NAS location until further notice. With a GS an immediate constraint can be placed on system demand, whenever an area, center, sector or airport experiences a significant reduction in capacity.

Therefore, while aircraft may wait in queues in front of an airport resource because of the resource capacity limitation (as described in Section 2.1), aircraft may also wait in queues in front of the airport resource due to capacity limitations at downstream resources, as implied by Figure 2.2. The air traffic controller may block the outbound flow from a resource under his or her control in order to maintain the level of traffic at downstream resources within safe and acceptable levels below capacity. This is insured through the different feedback and restriction mechanisms shown in Figure 2.2.
Chapter 3

Analytical framework

Using the controlled queuing model developed in Chapter 2 (Figures 2.1 and 2.2) as a physical representation of the departure process, a corresponding analytical framework is posed in this chapter based on common queuing notions. This analytical framework is then used to analyze the departure process queuing dynamics and control behavior, in later chapters.

3.1 The departure process system

Figure 3.1 depicts a generic departure process or sub-process as a black box system between an entry event and an exit event. A departure aircraft “i” enters the system by way of the entry event at time $t_{entry,i}$ and leaves the system by way of the exit event at time $t_{exit,i}$. The defined system encloses the set of aircraft operations performed between the entry and exit events.

![Figure 3.1: Departure process system](image_url)
Using this system representation, certain states of the departure process or sub-process and of the departure aircraft "i", can be defined at any time \( t \). For example, one state variable of a departure aircraft "i" is its time in the system \( D_i = t_{\text{exit},i} - t_{\text{entry},i} \), which is the time that the departure aircraft spends in the system between entry and exit. At any current time \( t \) between the entry and exit, \( D_i \) may represent the elapsed time in the system for the aircraft between its entry time and the current time, \( D_i(t) = t - t_{\text{entry},i} \). State variables of the departure process include, for example, the number of aircraft in the system at any time \( t \) (departure aircraft that had entered but did not exit yet at time \( t \)), and the average rates of the entry and exit events (over some time period \( \Delta t \)).

The desired analysis and the availability of measured events motivate the choice of the system and its boundary (the entry and exit events). Two systems that are analyzed in this thesis are the overall departure process between the pushback and takeoff events (Chapter 4), and departure sub-processes defined between certain controller/pilot communication events (Chapter 5). The pushback and takeoff events are measured by the ACARS\(^{10} \) Out and Off time events, by way of switches that are activated when the "doors are closed and the brakes are released" and when the "wheels are off", respectively. Controller/pilot communication events were recorded manually during field observations at Boston Logan Control Tower.

\(^{10}\) ACARS is the Air Carrier Automated Reporting System adopted by the major airlines.
3.2 Lumped element representation of the departure process

Depending on the choice of the entry and exit events, the departure process system in Figure 4.2 may consist of a single airport resource or of multiple airport resources. In order to pose a generic framework and because one is usually able to measure only the entry and exit events, the physical model presented in Figures 2.1 and 2.2 is used as a lumped element representation of the departure process or sub-process enclosed in the system analyzed. This representation is depicted in Figure 3.2, where all the resources in the system are lumped into a controlled resource element and all the queues in the system are lumped into a queuing element.

Figure 3.2: Lumped element representation of the departure process system
In order to identify the control behavior in the queuing dynamics, the control elements in the lumped element representation are kept explicit as shown of Figure 3.2. Namely, the clearance/hold switch is kept in front of the resource and multiple queues are included in the queuing element to represent the sequencing and suspending behavior. The ATC control actions are also lumped into a single control input from the air traffic controller(s) to the system.

3.3 Analysis of the time in the system

In order to identify the queuing dynamics, the time $D_i$ that a departure aircraft "i" spends in the system is analyzed in accordance with the lumped element representation of the departure process in Figure 3.2. Components of the time $D_i$ are associated with the queuing and control elements of the system. The control elements allow the isolation of the time components that are controllable by the air traffic controllers such that the control behavior can be identified.

3.3.1 Effective service and waiting components of the time in the system

Based on conventional queuing notions, the time that an aircraft spends in a queuing system is divided into two parts, a service time associated with the resource part of the system and a waiting time associated with the queuing part. Accordingly, the time $D_i$ that a departure aircraft "i" spends in the queuing system of Figure 3.2, is divided into an "effective" service time and an "effective" waiting time (defined below) that are associated, respectively, with the resource and the queue parts of the system. These time components include the effects of the control elements of the lumped-element representation in Figure 3.2; hence the term "effective". In the next section, the effects of the control elements on the time in the system are isolated in order to
identify the control behavior. First the effective service and effective waiting times are defined. (The following definitions are made with respect to a particular aircraft “i”; however, for convenience the subscript “i” is omitted):

The effective service time $ES$ is defined as the time that it would take a departure aircraft to travel in the system between the entry and exit events if the aircraft is unimpeded by any other departure aircraft. Although an aircraft may travel between the entry and exit events unimpeded even if other departure aircraft exist in the system, unobserved interactions due, for example, to waiting for air traffic controllers and for communication channels, may cause delays. Therefore, in order to avoid any interactions, a more conservative definition of the effective service time is the time that it would take a departure aircraft to travel in the system between the entry and exit events if the system is empty of any other departure aircraft.

The effective waiting time $EW$ is defined as the time that a departure aircraft spends in the system between the entry and exit events due to being impeded by other departure aircraft in the system. The effective waiting time is the total time that a departure aircraft spends queuing behind other departure aircraft in the system, whether physically on the surface or due to any interactions. For example, $EW$ also includes waiting for air traffic controllers and communication channels behind other departure aircraft in the system.

Therefore, the effective service time $ES$ is the “free-flow”\textsuperscript{11} part of the total time $D$ in the system, which is not impeded by other departure aircraft, while the effective waiting time $EW$ is the part

\textsuperscript{11} “Free-Flow” is a term used for the unimpeded travel time in a system, for example, (Hall [1991]).
of the total time $D$, which is caused by impedance by other departure aircraft in the system. The total time in the system is the sum of the two components: $D = ES + EW$.

### 3.3.2 Controllable components of the effective service and waiting times

The effective service and effective waiting times are termed "effective" because they may include components that are neither pure service (operating on a resource) nor pure waiting behind other aircraft. These components are associated with the control elements in the lumped-element representation of the departure process in Figure 3.2. For example, because of the switch representing the ATC clearance, the aircraft service may be interrupted even though the system may be empty of any other departure aircraft. Aircraft may also be suspended in the suspension area to absorb lengthy delays, while other departure aircraft pass it and use the system's resources. Therefore, controllable components in the effective service and waiting times are isolated, by associating them with the control elements of the lumped-element representation. These time components are termed "procedural" time components to reflect that they are controllable by the air traffic controllers, mainly implementing ATC procedures.

#### 3.3.2.1 Actual versus procedural service time

Referring to the lumped element representation in Figure 3.2, given that the system is empty of any other departure aircraft, the effective service time $ES$ that a departure aircraft spends in the system consists of two components: An **actual service time** $S$ which is defined as the total time that the aircraft spends operating on the resources of the system after the clearances are
delivered\textsuperscript{12}, and a \textbf{procedural service time} $S_P$ which is defined as the total time that the aircraft spends not operating on the resources of the system, even though the system is empty of any other departure aircraft, because it does not have a clearance to use the resources. Both time components $S$ and $S_P$ are part of the effective service time because they are incurred during free flow while the system is empty of any other departure aircraft. $S$ is spent operating on the resources of the system, while $S_P$ is spent being interrupted from operating. The total effective service time of a departure aircraft is the sum of the two components, $ES = S + S_P$.

The actual service time $S$ (which starts after the clearance is delivered) is determined by factors that are related to the aircraft operation on the resource, including aircraft performance, pilot behavior and resource conditions. While air traffic controllers were observed to encourage aircraft to speed up in some circumstances, the controller has hardly any control over the actual service time $S$ after the clearance is delivered\textsuperscript{1}. On the other hand, since the procedural service time $S_P$ precedes the delivery of the clearances, it is controllable by the air traffic controllers who can block the service\textsuperscript{13}. Control over $S_P$ may be implemented either by holding a clearance from an aircraft or by suspending the aircraft in a suspension area. (Since no other departure aircraft exist in the system, the effect of $S_P$ is identical whether the mechanism is holding the clearance or suspending in a suspension area).

For example, the departure process system may be defined between the event of the departure aircraft arrival to the runway end and the event of the wheels-off. for a single departure runway

\textsuperscript{12} It was observed that one clearance instruction may include multiple clearances and clear an aircraft to proceed to use a series of subsequent resources, as in clearing aircraft through a number of taxiway intersections and segments up to a holding point and instructing aircraft to follow each other. In these cases, when an aircraft arrives at the resource the clearance is already obtained.

\textsuperscript{13} The time $S_P$ may also be caused by uncontrollable interruptions that may be related to the aircraft (mechanical problems or internal delays) or related to the airport surface conditions.
at Logan Airport, an average observed time between successive takeoff clearances was 45 seconds when no landings, runway crossings or wake vortex separations intervened between the takeoffs (Idris 2001). This average may be considered an approximation of the average actual service time $\bar{S}$ for departures on the runway, since it represents mainly the runway occupancy time between the takeoff clearance and the wheels-off events. After delivering the takeoff clearance, the air traffic controller has no control over the time that an aircraft will occupy the runway. Before delivering the takeoff clearance, however, the Local controller may hold the departure aircraft (which is the first or the only one in the takeoff queue and therefore, is unimpeded by other departure aircraft) for a procedural service time $S_p$ in order to apply certain runway operation procedures. For example, if the Local controller decided to insert one or more runway crossings before the takeoff, the departure aircraft would be held for a procedural time $S_p$ prior to the takeoff clearance and its total effective service time would increase. In (Idris 2001) it was shown that the average time between the takeoff clearances increased to 2 minutes when runway crossings were inserted between takeoffs. The additional 1 minute and 15 seconds may be considered an approximation of the average procedural service time $\bar{S}_p$ of the departures on the runway caused by runway crossings. Similarly, other factors that cause increased runway effective service time for departures, such as landing aircraft, wake vortex separations, and controller workload, can be attributed to procedural service time components. Then improved system performance may be achieved through better control that reduces the departure interruption due to these procedural components.
3.3.2.2 FCFS versus procedural waiting time (Passing as indication of control)

As defined in the previous section 3.3.1, the effective waiting time $EW$ is the time that a departure aircraft spends in the system due to queuing behind other departure aircraft in the system. Each departure aircraft experiences a queue size $N$, which is the number of departure aircraft that exit from the system during the time $D$ that the departure aircraft spends in the system. The effective waiting time $EW$ of the departure aircraft is, therefore, caused (at least in part) by the queue size $N$ that it experienced: $EW(N)$. (The larger the queue size $N$, the larger is the chance of interaction and incurring delays because of queuing behind at least some of the $N$ aircraft).

Based on the lumped element representation of the departure process (Figure 3.2), the air traffic controllers may influence the effective waiting time of a departure aircraft by changing the queue size $N$ that it experiences, through sequencing. The air traffic controllers attempt to maintain a First Come First Serve (FCFS) sequence; however, they may allow a particular departure aircraft to pass some of the existing aircraft in the system and allow other departure aircraft that enter the system later to pass it. Passing may be allowed, for example, if an aircraft is an emergency that has to be expedited, or has an assigned takeoff time, or if some of the existing aircraft are suspended absorbing long delays. Passing may also be allowed due to the different distances between the gates and the runways or due to the sequencing strategies of the controllers who may deviate from the nominal FCFS sequence in order to improve efficiency or workload. Therefore, the effect of the control behavior on the effective waiting time of a departure aircraft manifests mainly through the sequencing behavior that deviates from a nominal FCFS sequence.
Therefore, similarly to the effective service time, the effective waiting time $EW$ is divided into two components that correspond to two components of the queue size $N$: a FCFS component and a passing component, as shown in Figure 3.3. In Figure 3.3, the queue size $N$ experienced by a reference departure aircraft is divided into two components: a FCFS component (of size $N_{FCFS}$) and a passing component (of size $N_P$). The FCFS queue component $N_{FCFS}$ consists of the departure aircraft that entered the system before the entry time of the reference aircraft and exited from the system during the time $D$ that the reference aircraft spent in the system. The passing queue component $N_P$ consists of the departure aircraft that entered the system after the entry time of the reference aircraft and exited from the system during the time $D$ that the reference aircraft spent in the system. The total queue size experienced by the reference aircraft is the sum of the two components, $N = N_{FCFS} + N_P$. Figure 3.3 also shows a number of departure aircraft $N^p$ that were passed by the reference aircraft. These aircraft entered the system before the entry time of the reference aircraft but exited from the system after the reference aircraft.

When the reference aircraft enters the system it finds a total of $N_0$ aircraft in the system. It passes $N^p$ of these $N_0$ aircraft and $N_{FCFS}$ aircraft remain ahead of it and exit from the system before it (i.e. $N_0 = N^p + N_{FCFS}$). The $N^p$ aircraft could have been part of the FCFS queue component $N_{FCFS}$ of the reference aircraft had they exited from the system before it. However, they were passed by the reference aircraft and therefore, they did not contribute to its queue size $N$ and did not affect its waiting time.
Figure 3.3: FCFS and passing queue components

Corresponding to the two components of the queue, the effective waiting time is also divided into two components: the FCFS waiting time $W_{FCFS}$ which is caused by waiting behind the FCFS component of the queue $N_{FCFS}$, and the procedural waiting time $W_P$, which is caused by waiting behind the passing component of the queue $N_P$. Therefore, the effective waiting time $EW$ for a departure aircraft, is the sum of the FCFS waiting time and the procedural waiting time, each a function of the queue size that causes it: $EW(N) = W_{FCFS}(N) + W_P(N_P)$. 
The passing queue component, therefore, causes a procedural waiting time $W_P$ in excess of the FCFS waiting time $W_{FCFS}$. Control of $W_{FCFS}$ is possible only to the extent that the air traffic controller can control the size of the FCFS component of the queue $N_{FCFS}$ (most of which may be already at the runway end, beyond any possible resequencing). On the other hand, the procedural waiting time $W_P$, like $S_P$, is controlled mainly by the control actions of the air traffic controllers (namely, through sequencing, suspending and routing).

Hence, loss of system performance in terms of incurring delays can be attributable to any of the four system time components: $S$, $S_P$, $W_{FCFS}$ and $W_P$. For example, flow constraints may cause delays to an aircraft through one or more of the components of the time in the system. However, the losses due to the procedural time components, $S_P$ and $W_P$, are the ones that are potentially controllable, and could be improved upon through better control. This is depicted in Figure 3.4 where the system queuing dynamics are represented in terms of the time in the system $D$ and its components as a function of the queue size. The control actions of the controllers are shown to affect mainly, $S_P$, $W_P$ and the queue size including the passing aircraft $N_P$ and to a lesser extent, $N_{FCFS}$.

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14 By dividing the effective waiting time $EW$ of a reference departure aircraft into two components, $W_{FCFS}$ and $W_P$, it may appear that passing always causes an increase in the reference aircraft’s effective waiting time through the procedural component $W_P$ (which is caused by allowing other departure aircraft to pass the reference aircraft). However, passing also saves the reference aircraft waiting time by allowing it to pass some of the aircraft $N_P$ that existed in the system at its entry time. These passed aircraft $N_P$ would have caused additional FCFS waiting time, since the assumed nominal FCFS sequencing behavior would have sequenced the reference aircraft behind all the existing ones at entry time. Therefore, passing has two effects on the waiting time of each aircraft: one that increases the waiting time due to allowing other aircraft to pass it and one that reduces the waiting time by allowing the aircraft to pass other aircraft. The two effects should nullify each other when averaged over all aircraft since for each aircraft that passes another aircraft, there is an aircraft that is passed.
Figure 3.4: Analysis and control of the time in the system

Using the analytical framework posed in this chapter, the departure process queuing dynamics are analyzed in the next three chapters under different scenarios. In Chapter 4, the overall departure process between pushback and takeoff is analyzed and passing is used as an indication of the non-FCFS sequencing in the queuing dynamics. The overall relationship between the time in the system and the queue size is demonstrated including its two components attributed to FCFS sequencing and to passing. In Chapter 5, four departure sub-processes, defined between controller/pilot communication events, are analyzed using the same queuing framework, using passing again as indication of the control behavior. It is shown that the control opportunity decreases in the runway phase, which exhibits mainly FCFS queuing dynamics. Finally, in Chapter 6, the queuing dynamics are analyzed for aircraft that are affected by downstream restrictions, indicating the difference in the queuing and control behavior under different types of restrictions.
Chapter 4

Queuing dynamics of the overall departure process

In this Chapter the overall departure process, defined between the pushback and wheels-off events, are analyzed based on the framework posed in Chapter 3. In addition to demonstrating the analytical framework, the analysis of the overall departure process identifies the overall queuing and control behavior and provides a basis for comparison with the dynamics of departure sub-processes and the dynamics under the effect of downstream restrictions, which are analyzed in the next two chapters.

4.1 Analysis of the time in the system (taxi out time)

As shown in Figure 4.1, each departure aircraft enters into the overall departure process system at its Out time as measured by the ACARS “doors closed and brakes released” event and exits from the system at its Off time as measured by the ACARS “wheels-off” event. The time $D$ that the aircraft spends in the system ($D = \text{Off time} - \text{Out time}$) is referred to as the taxi out time.
Figure 4.1: Overall departure process system based on the ACARS measurements

The taxi out time $D$ is analyzed according to the framework developed in Chapter 3, identifying the main time components and their relationship to the queue size $N$ experienced by each aircraft. The queuing dynamics were analyzed for a sample of one month of ASQP data (July 1998)\textsuperscript{15}. The sample was divided into two sub-samples: departure aircraft that were not passed ($N = N_{\text{FCFS}}$ and $N_P = 0$), from which the waiting time due to FCFS queuing ($W_{\text{FCFS}}$) was identified, and departure aircraft that were passed ($N = N_{\text{FCFS}} + N_P$ and $N_P > 0$), from which the waiting time due to passing ($W_P$) was identified.

4.1.1 FCFS queuing dynamics

The FCFS queuing dynamics were analyzed by identifying the relationship between the taxi out time and the queue size for the sample of aircraft that were not passed ($N = N_{\text{FCFS}}$ and $N_P = 0$). Since the aircraft in this sample experienced only a FCFS queue, their effective waiting time consisted entirely of the FCFS waiting time ($W_{\text{FCFS}}$) with no procedural waiting time ($W_P = 0$

\textsuperscript{15} The analysis was performed without distinction between the runway configurations that were used in July 1998. Also there was no accounting for the dynamics of the airlines other than the 10 included in the ASQP data (about 50\% of the total traffic at Logan Airport).
since \( N_p = 0 \). In Figure 4.2, the average taxi out time (computed over the aircraft that experienced the same queue size, \( N_{FCFS} \)) is plotted as a function of the queue size \( (N_{FCFS}) \). Figure 4.2 also shows the range of taxi out times at each queue size and the frequency distribution of the queue size. The average effective service time and the average effective waiting time are identified on the plot as discussed below.

![FCFS Queuing Dynamics](image)

**Figure 4.2: FCFS queuing dynamics**

### 4.1.1.1 The effective service time

The zero intercept of the average taxi out versus queue size curve in Figure 4.2 (11:41 minutes) is the average taxi out time for the aircraft that experienced a zero queue size. Therefore, the zero intercept represents the average effective service time \( (\bar{ES}) \), which is (as defined in Chapter
3) the average travel time that an aircraft would spend in the system between the Out and Off times if unimpeded by any other departure aircraft. The average effective service time includes two components (as shown in Figure 4.2): the average actual service time \( \bar{S} \) when the aircraft were operating on the airport resources and the average procedural time \( \bar{S}_p \) when the aircraft were not operating because they were held by not obtaining the clearances from the air traffic controllers or by being suspended. (These two components cannot be separated in this analysis).

Figure 4.3 shows the frequency distribution of the effective service time \( (ES) \), with an average of 11:41 minutes and a standard deviation of 3:13 minutes. The variability in the effective service time is caused by factors such as the speed of the aircraft, the distance between the gate and the runway, the pilot's behavior, the airport surface conditions as well as any occurrences or restrictions that may have interrupted any of the aircraft operations. The variability is also caused by factors such as the traffic of the airlines not included in the ASQP data and the different runway configurations (which are not accounted for in this analysis). (These factors are also present in the taxi out time distributions at each value of the queue size in Figure 4.2).
4.1.1.2 The marginal system time

As shown in Figure 4.2, the average taxi out time of the aircraft that faced a queue size larger than zero is divided into two components: the zero intercept and the vertical offset from the zero intercept to the average taxi out time value on the curve. The zero intercept is the average effective service time, which represents the average taxi out time that these aircraft would have spent if they had experienced no queuing. While the vertical offset represents the average FCFS waiting time ($W_{FCFS}$) that was incurred by these aircraft because of the FCFS queue (of size $N_{FCFS}$) that they experienced. The average taxi out time increases with the queue size in Figure 4.2 as expected, where the slope of the curve represents the average marginal waiting time that a departure aircraft spends in the system due to each additional aircraft in its queue.
Note: The overall departure process between pushback and takeoff is a complex queuing network. Therefore, the queue that a departure aircraft experiences (during its taxi out) is the number of aircraft in the entire queuing network and may consist of aircraft in multiple interacting queues. If the queue size is small (for example 1 or 2 aircraft), queuing may not occur since these aircraft may take off without any interaction with the reference aircraft in any of the individual queues of the queuing network. As the queue size increases, the probability of interacting with the other aircraft, and hence incurring additional waiting time due to queuing, increases. As this probability of interaction and queuing increases, the average marginal waiting time due to each additional aircraft in the queue also increases. Therefore, the slope of the curve of the average taxi out time versus queue size (in Figure 4.2) increases with the queue size. However, the slope should reach a maximum value, which reflects the saturation of the system’s throughput at a maximum value as the queue size increases\(^{16}\) (see for example, Cassandras, Figure 6.17).

4.1.2 Passing dynamics

The effect of passing on the queuing dynamics of the overall departure process was analyzed for the sample of aircraft that were passed \((N = N_{\text{FCFS}} + N_P \text{ and } N_P > 0)\). As described in Section 4.1, the aircraft that are passed incur a procedural waiting time \((W_P)\) caused by the passing queue component \((N_P)\) in addition to the FCFS waiting time \((W_{\text{FCFS}})\), which is caused by the FCFS queue component \((N_{\text{FCFS}})\). This is demonstrated in Figure 4.4, where the taxi out time of the

\(^{16}\) As \(N_{\text{FCFS}}\) grows, more pressure is exerted on the system’s resources and the throughput of the system approaches a maximum rate capacity (see for example Shumsky for Logan Airport). Consequently, the average marginal waiting time (which is the slope of the curve in Figure 4.7) approaches the minimum time possible between successive departures from the system, which is one over the system’s maximum throughput (see for example, Cassandras for a closed queuing system with increasing population, Figure 6.17).
passed aircraft (which experienced a FCFS and a passing queue component) is compared with
the taxi out time of the non-passed aircraft (which experienced only a FCFS queue component).
In order to compare the two samples, the average taxi out time of both samples is plotted versus
the size of the FCFS queue component (which for the non-passed aircraft is the total queue size
while for the passed aircraft is only part of the total queue size). The non-passed aircraft curve is
the same one shown in Figure 4.3 and it approximates the average taxi out time that a passed
aircraft would have incurred had it not been passed. It is clear from Figure 4.4 that the passed
aircraft spent an additional time taxiing out given by the vertical offset between the two curves.
Therefore, the vertical distance between the two curves is an approximation of the average
procedural waiting time \( \overline{W}_p \), which is caused by the passing queue component \( N_p \) of the
queue.

![Passing and FCFS Components of Taxi Out Time](image)

**Figure 4.4: FCFS and passing waiting time components**
In Figure 4.5, the overall dynamics curve, which relates the average taxi out time to the total queue size \((N)\), where \((N = N_{FCFS} + N_P)\), (for all aircraft), is superimposed on the two curves of the passed and non-passed aircraft of Figure 4.4. The components of the taxi out time are demonstrated for a typical data point (aircraft) that is assumed to lie on the overall dynamics curve with an average total queue size and an average taxi out time.

![Passing and FCFS Components of Taxi Out Time](image)

**Passing and FCFS Components of Taxi Out Time**
(Source: Logan Airport, ASQP data, July 1998)

- Passed aircraft (plotted versus FCFS part of their queue \(N_{FCFS}\))
- All aircraft
- Aircraft not passed
- \(N_{FCFS}\)
- \(W_P\)
- \(W_{FCFS}\)
- \(ES = \bar{S} + \bar{S}_P\)

**Figure 4.5: Components of the queue and taxi out time for a typical aircraft**

The typical data point shown in Figure 4.5 is an aircraft that experienced a total queue size of 12 aircraft, composed of two components: a FCFS queue component of 9 aircraft and a passing queue component of 3 aircraft (such that it lies also on the passed-aircraft curve). Given that the FCFS queue size was 9 aircraft, the non-passed aircraft curve approximates the components of
the taxi out time that are attributed to effective service or free-flow (the zero intercept), and the FCFS waiting time component (as shown in Figure 4.5). Then the vertical offset between the non-passed-aircraft and the passed-aircraft curves approximates the waiting time incurred due to the passing part of the queue.

**Note:** Figure 4.5 shows that the overall dynamics curve almost coincides with the non-passed aircraft curve. This is expected since in both curves the average taxi out time is plotted versus the total queue size \( (N) \) that aircraft experienced, while the passed-aircraft curve relates the average taxi out time to only part of the total queue (namely the FCFS part, \( N_{FCFS} \)).

Therefore, the passed aircraft spent an average procedural waiting time \( (W_{P}) \) in taxi out, either due to being passed or which resulted in being passed by \( (N_{P}) \) passing aircraft, in addition to the FCFS waiting time, which is caused by the FCFS component of the queue \( (N_{FCFS}) \). This additional waiting time is indicated on an aggregate level in Figure 4.6, which displays the frequency distribution of the taxi out time for the full sample of aircraft, divided into the two sub-samples: the departure aircraft that were passed and the departure aircraft that were not passed. The average taxi out time of the non-passed aircraft was 17:19 minutes (with a standard deviation of 5:55 minutes), while the average taxi out time of the passed aircraft was 25:50 minutes (with a standard deviation was 13:48 minutes). The two sub-samples combined result in an overall average taxi out time of 20:21 minutes with a standard deviation of 10:21 minutes.

The excess taxi out time spent by the passed aircraft was due to the larger queue size experienced by these aircraft. The average queue size experienced by the non-passed aircraft (which consisted only of a FCFS component) was 4.5 aircraft with a maximum of 16 aircraft as was shown in Figure 4.2. On the other hand, the average queue size experienced by the passed aircraft was 7.4 aircraft, 5.3 of which was the average size of the FCFS component and 2.1 the
average number of the passing aircraft. It should be noted that these averages are for ten major airlines represented in the ASQP data in the month of July 1998 and over all runway configurations.

![Taxi Out Time (Passed vs Non-Passed Aircraft)](image)

**Figure 4.6:** Passing effect on taxi out time

### 4.2 Insights about the overall queuing dynamics

In Section 4.1, the analytical framework developed in Chapter 3 was applied to the overall departure process between pushback and takeoff, and the taxi out time was analyzed by identifying its components: the free-flow, effective service time and the waiting time. The free-flow time includes both the time of operation and any procedural interruption of operation by the air traffic controllers and the waiting time was divided into a FCFS and a passing component. Therefore, in addition to the free-flow time, a departure aircraft incurs a marginal taxi out time
due to each departure aircraft in its queue, whether it is a FCFS sequenced aircraft or a passing aircraft. The overall result is the queuing dynamics shown in Figure 4.7 in terms of the relationship between the average taxi out time and the total queue size \( N \) which consists of the two, FCFS and passing components \( N = N_{FCFS} + N_P \). Three curves are displayed in Figure 4.7, the average and the standard deviation of the taxi out time as a function of the queue size \( N \) and the frequency of \( N \). These curves will be analyzed in the next subsections.

![Overall Queuing Dynamics](image)

**Figure 4.7: Overall queuing dynamics**
4.2.1 Passing and control behavior

The frequency distribution of the queue size ($N$) in Figure 4.7 shows that, on average, a departure aircraft experienced a queue size of 5.6 aircraft. This total queue size included a FCFS component ($N_{FCFS}$), which had an average size of 4.8 aircraft, and a passing component ($N_{p}$), which accounted for the remaining 0.8 aircraft of the queue. Therefore, the queueing dynamics at Logan airport indicate a dominant FCFS sequencing behavior and limited resequencing. In addition, passing is observed more often as the size of the total queue size ($N$) and the taxi out time increase. This is shown in Figure 4.8, which compares the relationship between the average taxi out time and the total queue size ($N$) for all aircraft in July 1998 and for the two subsamples: the passed aircraft and the non-passed aircraft.

Figure 4.8: Relative effect of passing on the queueing dynamics
The taxi out time versus queue size curve of all-aircraft coincides with the non-passed-aircraft curve at the zero intercept and at small queue size values. Then it separates from the non-passed-aircraft curve and approaches the passed-aircraft curve, eventually coinciding with it at large queue size values. Therefore, the aircraft that experienced small queue sizes were mainly non-passed aircraft, while the aircraft that experienced larger queue sizes were mainly passed aircraft. In fact, the maximum size of the FCFS queue component ($N_{FCFS}$), over the full sample, was 17 aircraft. Therefore, the larger queue sizes in Figure 4.7 (which had a peak value of 45 aircraft) and the corresponding large taxi out times (which had a peak value of 229 minutes) were attributed mainly to the passing component ($N_P$). These aircraft were probably suspended for a long delay while being passed by other departure aircraft.

Another observation from Figure 4.8 is that the average taxi out time versus queue size curve for the passed aircraft lies above the same curve for the non-passed aircraft and for all aircraft. Therefore, for the same queue size ($N$), the passed aircraft incurred additional taxi out time that is not explained by waiting for the queue size. This additional taxi out time must be attributed to factors other than the marginal system time caused by waiting for each aircraft in the queue. Figure 4.9 relates the average taxi out time to the number of aircraft that passed an aircraft during its taxi out (the size of the passing queue component ($N_P$)). It shows also that the marginal taxi out time incurred due to each additional passing aircraft was about 4.1 minutes per aircraft. This is much larger than the marginal taxi out time for the non-passed aircraft, which was 1.8 minutes per each aircraft of the FCFS queue ($N_{FCFS}$) (the slope of the curve in Figure 7.2)\textsuperscript{17}. Therefore,

\textsuperscript{17} The marginal rates are computed using simple linear trend. Also, to reduce the effect of the variability in the FCFS queue component, the marginal taxi out time was computed also for the sub-sample that had a constant FCFS queue size of 4 aircraft, and was also higher than 3 minutes per passing aircraft.
passed aircraft incurred excessive taxi out times beyond what was needed to wait for the queue size.

![Graph showing the passing effect on taxi out time](image)

**Figure 4.9: Marginal taxi out time as a function of the number of passing aircraft \( N_p \)**

As described in Chapter 3, there are a number of reasons why passing may occur. For example, passing may take place by merging ahead of other aircraft taxiing out, due to the different distances between the gates and the runways. Passing may also occur due to taking off from different runways in an order that is different from the pushback order. Passing may be forced by the air traffic controllers through sequencing while attempting to improve efficiency or to comply with certain restrictions. Finally passing may result from suspending aircraft for a long delay, such as due to a ground delay program or due to a mechanical problem, while during suspension, other aircraft may pushback and pass the suspended aircraft. When passing occurs within a busy period of the departure runways, passing simply alters the composition and size of
the queue that the aircraft sees; however, the effective waiting time of the aircraft should remain the accumulated marginal system times caused by waiting for each aircraft in the queue. However, when an aircraft is suspended for a long period of time, it may see some idle periods at the departure runways, and the number of aircraft that pass it reflect the rate at which departure aircraft enter the system (i.e. pushback) during the suspension period\(^{18}\). Figure 4.10 shows how the passing behavior is a function of the taxi out time. Aircraft that spent less than 15 minutes taxiing \(t_{\text{in}}\) were hardly passed by other aircraft, while they passed other aircraft more often. On the other hand, as the taxi out time increased, the number of passing aircraft increased at a rate of about six minutes per aircraft.

Figure 4.10: Passing as a function of the taxi out time

\(^{18}\) If an aircraft was suspended for a time \(T\) during which the departure aircraft were entering the system (pushing back) at an average rate \(\lambda\), then the average number of passing aircraft is \(\lambda T\).
Therefore, the large marginal taxi out time per passing aircraft \(N_P\) is a manifestation of long suspensions of the passed aircraft and the slope is a reflection of the arrival rate of departure aircraft during the suspension period rather than the system’s service rate capacity.

**Note:** it should be more accurate, therefore, to estimate the system’s rate capacity from the sample of aircraft that are not passed, which have less probability of meeting idle periods of the runways.

While the cases of large queue sizes and more passing aircraft may indicate suspension of taxiing under special circumstances, the small average (0.8 aircraft) of the number of aircraft that passed another aircraft \(N_P\) is indicative of a moderate level of sequencing. Such common sequencing behavior is caused mainly by the variant distances between the gates and the runways as well as by the common sequencing strategies of the air traffic controllers, who may deviate from the FCFS strategy as was described above. It was also shown that while a departure aircraft was passed on average by 0.8 other departure aircraft, it also passed on average 0.8 other departure aircraft. Therefore, while passing causes a procedural waiting time due to the passing aircraft, it also saves the aircraft a FCFS waiting time due to the passed aircraft. The two effects are identical in absolute value since for every passing aircraft there is a passed aircraft.

### 4.2.2 The variability in the taxi out time

Referring to the taxi out frequency distribution in Figure 4.6, the overall standard deviation in the taxi out time was 10:21 minutes. This high variability is attributed in part to non-modeled dynamics and factors. For example, the uncertainty may be improved by analyzing the dynamics under specific runway configurations, under specific weather conditions and possibly under particular air traffic controllers. The ASQP data also ignores about 50 percent of the traffic at
the airport since only 10 major airlines report the ASQP data. Delcaire and Pujet showed that it is possible to reduce the error in estimating the taxi out time to about 5 minutes if estimated for a specific runway configuration and specific airline (general gate location). The standard deviation curve in Figure 4.7 shows the variability in the taxi out time as a function of the queue size. Knowledge about the queue size reduces the uncertainty as shown in Figure 4.7, where the standard deviation ranged between 3:13 minutes for $N = 0$, to 5:55 minutes for $N = 10$ aircraft, to 11:40 minutes for $N = 20$ aircraft. (Taking factors such as the runway configuration and the airlines into account should reduce these values further). However, the standard deviation increases with the queue size, as additional aircraft in the queue add more variability in the taxi out time.

The high variability in the taxi out time is a major constraint in attempting to predict the takeoff time of an aircraft. Estimating the takeoff time is essential for the air traffic controllers who often need to comply with restrictions that require aircraft to takeoff within a specific time window. Two examples of such restrictions are the Estimated Departure Clearance Time (EDCT), which is imposed through the Ground Delay program; and the Departure Sequencing Program (DSP) which is imposed through the ATC center in charge of the airspace surrounding the airport (see Chapter 2). EDCT assigns a departure aircraft that is heading to a restricted destination airport a takeoff time with a window of 15 minutes (5 minutes ahead of to 10 minutes later than the assigned time). DSP assigns a departure aircraft that is heading to a restricted airspace sector, a fix or a destination airport, a takeoff time with a three-minute window (3 minutes later than the assigned time). Accurate prediction of takeoff times helps the air traffic controllers in sequencing the aircraft in the right order in the takeoff queue in order to comply
with such restrictions. It is also essential for automated tools that attempt to assist the air traffic controllers in managing the departure traffic, especially under such restrictions.

When an aircraft is introduced into the system at pushback, the queue size may be observed at the pushback time (the number of aircraft taxiing at pushback time \((N_0)\)), and the taxi out time may be predicted based on its size. However, the size of the actual queue \((N)\) that the aircraft eventually experiences before takeoff may differ from the size of the queue at pushback time \((N_0)\), because of passing \((N_0 = N_{FCFS} + N_P\) while \(N = N_{FCFS} + N^p\)). The queue size seen by an aircraft at pushback time \((N_0)\) and the actual queue size \((N)\) experienced by the aircraft have exactly the same mean value (5.6 aircraft in the sample of July 1998). This is expected because the average number of aircraft that are passed by an aircraft \((\bar{N}^p)\) and the average number of aircraft that an aircraft passes \((\bar{N}_P)\), are equal (0.8 aircraft in the sample of July 1998). However, although the queue size at pushback time and the actual queue size have the same mean value, they would differ for each particular aircraft depending on its circumstances\(^{19}\). For example, Figure 4.11 shows that passing is a function of the queue size at pushback time \((N_0)\). The larger the queue size observed at pushback time, the larger the number of aircraft \((N^p)\) that an aircraft passes. On the other hand, the number of aircraft \((N_P)\) that pass a particular aircraft during its taxi out is not strongly a function of the queue size at pushback time. Figure 4.10 showed, however, that the number of passing aircraft \((N_P)\) is strongly a function of the duration of taxi out. Therefore, if an aircraft is expected to have a longer taxi out time, due to a longer

\(^{19}\) Even though the means are equal for the number of aircraft that are passed by an aircraft and the number of aircraft that pass an aircraft, their standard deviations are different: 1.1 passed aircraft versus 1.8 passing aircraft. This is because a small number of suspended aircraft (for a long delay) may be passed by a large number of other aircraft increasing the standard deviation of the number of passing aircraft.

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distance from its gate to the runway or due to a known restriction such as a ground delay, it would be expected to be passed by a larger number of aircraft ($N_p$).

Figure 4.11: Passing as a function of the queue size at pushback time ($N_0$)

Therefore, by taking the relationships in Figure 4.11 into account one may be able to predict the taxi out time and the takeoff time with better accuracy, based on a more accurate prediction of the actual queue size ($N$). For example, Figure 4.12 compares the standard deviation in the taxi out time as a function of the queue size at pushback time ($N_0$) and of the actual queue size ($N$), which includes the FCFS and passing components. There is clearly a higher uncertainty in the taxi out time based on the queue size at pushback time ($N_0$), which may be improved upon by taking passing into account and predicting the actual queue size ($N$) for each aircraft.
Figure 4.12: Variability in taxi out time as a function of the queue size

Note: The air traffic controllers monitor as well as can affect the queue size experienced by a particular departure aircraft in real time. Therefore, the levels of uncertainty that they face may be less than what is indicated in Figure 4.12, for example.
Chapter 5

Queuing dynamics of the communication-based departure sub-processes

In this chapter controller/pilot communication data, which was collected during field observations at Logan Airport, is analyzed in order to compare the queuing dynamics and control behavior in four departure sub-processes, according to the queuing framework described in Chapter 3.

5.1 Methodology

Five main communication events (the pilot’s call “ready for pushback” (if jet) or “ready for taxi” (if prop) and four controller instructions: "clear for pushback," "clear for taxi," "monitor tower" and "clear for takeoff") were recorded manually during field observations at Logan Control Tower. The four departure sub-processes defined between the recorded communication events are used as surrogates for four main operational phases in the departure process (the gate, ramp, taxi and runway phases). According to the framework developed in Chapter 3, each communication-based sub-process is represented with a lumped element representation consisting of a resource (representing the resources in the sub-process such as gates, ramp, taxiways or runways) and a queue (representing the queues in the sub-process) (see Figure 5.1 and 5.2).
A sample of eight hours of controller/pilot communication data collected in a single runway configuration (27/22L-22R/22L\(^{20}\)) and during high traffic periods was analyzed. The queuing dynamics of each sub-process were analyzed in terms of the relationship between the time spent and the queue size experienced by each aircraft in each sub-process as shown in Figure 5.1. The time in each sub-process is the duration between the starting and ending communication events, and the queue size experienced by a reference aircraft in a sub-process is the number of aircraft whose exit event from the sub-process lies between the entry and exit events of the reference aircraft (see Figure 3.3). Two plots are displayed in Figure 5.1 for each communication-based sub-process: the average time in the sub-process as a function of the queue size and the frequency distribution of the queue size.

Figure 5.2 shows the distribution of the time in each of the communication-based sub-processes. In order to gain insight about the sequencing and control behavior in the different departure phases (which are represented by the communication-based sub-processes), the sample was divided into the passed and non-passed aircraft (similarly to the analysis in Chapter 4). In Figure 5.2 the time distribution is shown for the two sub-samples, comparing the time incurred by the aircraft that were passed with the time incurred by the aircraft that were not passed. Some of the insights about the queuing and control behavior gained from the analysis in Figures 5.1 and 5.2 are discussed in the next two subsections.

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\(^{20}\) Land runways 27 and 22L - Depart runways 22R and 22L.
Figure 5.1: Queuing dynamics of the communication-based sub-processes
Figure 5.2: Time in the system of the communication-based sub-processes
5.2 Time versus queue size dynamics

The average time versus queue size curves in Figure 5.1 demonstrate the effective service time and the effective waiting time that each aircraft spent in each of the communication-based departure sub-processes (or corresponding departure phases). The average effective service time, is the zero intercept of each curve in Figure 5.1, and is the average free-flow time that an aircraft spent in each phase when unimpeded by other departure aircraft. This free-flow, effective service time in each phase consists of an actual service time representing time spent operating on the resources of the phase and a procedural service time representing any interruption of service by the air traffic controllers. In addition to the effective service time, aircraft spent in each phase an average effective waiting time, which is the vertical offset between the zero intercept and the curve. The average effective waiting time increases with the queue size as shown in Figure 5.1.

The effective waiting time consists of a FCFS waiting time due to the FCFS component of the queue experienced by each aircraft, and a procedural waiting time (in excess of the FCFS waiting time) which results from waiting behind passing aircraft. Figure 5.2 shows the distribution of the time spent in each phase or sub-process, where the sample is divided into the passed and non-passed aircraft for comparison. The passed aircraft form the tails of each distribution indicating the higher waiting time spent by the passed aircraft.

The effective service time in the pre-pushback phase (which includes jet aircraft only since props do not pushback) consists mainly of a procedural service time because during this time the aircraft does not perform any actual operation. Rather, in this phase the aircraft simply waits for the handoff process from the Gate controller who receives the "ready for pushback" call to the Ground controller who delivers the pushback clearance. The aircraft, therefore, incurs a
procedural delay caused by the air traffic controllers delay in the handoff process and any holding of the aircraft on the gate due, for example, to imposed restrictions or aircraft preparation problems. For example, while the average time in this phase was only 2 minutes and 38 seconds (from Figure 5.2), two aircraft spent 48 and 84 minutes between the first time that the pilot called “ready for pushback” and the pushback clearance. During this long delay, 23 and 45 other aircraft (respectively) received their pushback clearances prior to these two aircraft, as shown in Figure 5.1. Most of these aircraft were clearly passing aircraft (aircraft that called ready later). It should be noted that, except in such special circumstances that require holding on the gate, the pushback clearances (as observed) are delivered based on a strictly FCFS sequence at Logan Airport. This is motivated mainly by fairness to the different airlines that compete for the pushback clearance.

While the time spent in the pre-pushback phase is mainly a procedural delay, the queuing dynamics of the ramp, taxi and runway phases include actual service times for performing certain operations. For example, in the ramp phase, the effective service time for jets includes the pushback operation and the engine start. For props, however, the ramp phase consists mainly of a procedural time representing the duration of the handoff process from the Gate controller who receives the “ready for taxi” call to the Ground controller who delivers the taxi clearance (similarly to the pre-pushback phase for jets). The actual service time in the taxi and runway phases consists mainly of the duration needed for taxiing from the “clear for taxi” event to the “monitor tower” event (in the taxi phase) and from the “monitor tower” event until the “clear for

21 At most airports other than Logan the pushback clearance is under the airlines’ control. At Logan however, the ATC Tower was delegated the responsibility of delivering the pushback clearance, because of the intrusion of the pushback process on movement areas, such as taxiways, which are under the ATC Tower control, and in order to resolve conflicts between airlines that share a gateally according to a FCFS strategy.
takeoff” event (in the runway phase). Any ATC procedural interruptions of these operations (such as interruptions of pushback in the ramp phase or interruption of taxiing in the taxi and runway phases) contribute as procedural delays to the effective service times in the ramp, taxi and runway phases.

Figures 5.1 and 5.2 indicate that the delays are incurred mainly in the runway phase. The queue size frequency distributions in Figure 5.1 show that, on average, an aircraft queued behind 7.75 other aircraft in the runway phase, while in the taxi and ramp phases the mean queue size was below 4 aircraft, and only 1.26 aircraft in the pre-pushback phase. Corresponding to the largest queue size, aircraft incurred the largest average time in the runway phase as shown in Figure 5.2. The average time in the runway phase was 9:40 minutes, more than twice the average time in the taxi phase, which was 4:28 minutes and compared to only 3:48 minutes in the ramp phase and 2:38 minutes in the pre-pushback phase. From Figure 4.12, the average effective service time (the zero intercepts) for the four phases were comparable to each other (1:53 minutes in the runway phase, 2:08 minutes in the taxi phase, 1:35 minutes in the ramp phase and 1:29 minutes in the pre-pushback phase). Therefore, the average effective waiting time (which is the average total time minus the average effective service time) was also largest in the runway phase (8:47 minutes, compared to 2:20 minutes, 2:13 minutes, and 1:09 minutes in the taxi, ramp and pre-pushback phases respectively). This indicates that the larger delays incurred in the runway phase were caused mainly by longer queuing and waiting rather than by longer service time needed for operations.
5.3 Control points and opportunities

By comparing the number of aircraft that were passed and not passed in each of the phases in Figure 5.2, it is clear that a smaller percentage of aircraft were passed in the runway phase relative to the preceding phases. This indicates a dominance of a FCFS sequencing behavior and a decrease in resequencing of aircraft in the runway phase.

The dominance of the FCFS behavior over passing in the runway phase indicates that as aircraft entered the runway phase system the opportunity for control of the aircraft sequence by the air traffic controllers decreased. This is particularly true in the 27/22L-22R/22L runway configuration where the runway system consists mainly of a single takeoff queue that forms at the main departure runway, 22R. In fact, most aircraft that were passed in the runway phase were aircraft that requested or were assigned to runway 22L, which is primarily a landing runway, and had to wait for a longer time while aircraft that entered the runway phase later continued to take off on runway 22R. Also, in some cases penalty boxes available at the runway 22R end are used to hold delayed or restricted aircraft, while other aircraft pass them. However, the gate, ramp and taxiway phases offer much more opportunity to sequence, route and suspend aircraft prior to their entry into the runway takeoff queue.
Chapter 6

Queuing dynamics under downstream flow constraints

Downstream restrictions are one of the major factors that cause departure flow constraints and drive the strategies of the air traffic controllers in managing the aircraft movement through sequencing and suspending (Idris). In this chapter the queuing dynamics of the departure process under downstream restrictions are analyzed using the queuing framework posed in Chapter 3.

6.1 Methodology

The average taxi out time (Out to Off time as measured by the ACARS/ASQP data) versus queue size relationship was analyzed for samples of aircraft under no restriction and under four different types of restrictions:

- Departure Sequencing Program (DSP), which is a 3-minute takeoff time window restriction

- Expected Departure Clearance Time (EDCT), which is a 15-minute takeoff time window restriction

- Miles or Minutes In Trail, which are In-Trail spacing requirements between takeoffs and

- Ground Stop (GS), which is a time delay restriction until further notice.
(See Section 2.2 in Chapter 2 for a more detailed description of the restrictions)

Restriction data were obtained from the Logan Control Tower logs, which recorded each restriction type, its duration and its destination. A departure aircraft was considered restricted if there was an overlap between its taxi out time and the duration of a restriction to its destination. Local restrictions, which are imposed on the outbound traffic through exit fixes of the airport, were assumed to affect all aircraft taxiing during the restriction. The analysis was conducted for the sample of ASQP data in the month of July 1998.

6.2 Queuing dynamics under different downstream restrictions

Figure 6.1 shows the relationship between the average taxi out time and the queue size (N) for samples of aircraft that suffered no restriction, or one of the four types of restrictions mentioned above (Section 6.1). The average taxi out time versus queue size curve for all aircraft in July 1998 (from Figure 4.7) is included in Figure 6.1 for comparison, representing the nominal queuing dynamics of the overall departure process. As evident from Figure 6.1, the average taxi out time versus queue size curves of the aircraft that suffered no restriction as well as of the aircraft that suffered DSP, EDCT and IN-Trail type restrictions almost coincided with the overall curve of all aircraft. On the other hand, the aircraft that suffered GS restrictions deviated from the nominal all-aircraft curve and accounted for most of the suspended aircraft that experienced excessive queue sizes and taxi out times (except for one case of an EDCT restriction).
Figure 6.1: Queuing dynamics under downstream restrictions

Therefore, Figure 6.1 demonstrates a main difference between the time window (DSP and EDCT) or time spacing (IN-TRAIL) type restrictions and between the time delay type restriction (GS). In general, the effect of the latter is clearly larger in terms of causing excessive taxi out time and longer queues. But in addition, the fact that the DSP, EDCT and IN-TRAIL curves almost coincided with the all-aircraft queuing curve suggests that these two types of restrictions (time window and time spacing) were implemented mainly through sequencing (inserting the appropriate number of aircraft ahead of or in between restricted aircraft). The GS curve, on the other hand, deviated substantially from the all-aircraft nominal queuing curve, even at small queue size values. This suggests that aircraft that suffered a GS restriction were often delayed.
beyond the time needed to wait for the queue. During these long delays, the departure runway experienced idle periods since there was not enough demand to pass the restricted aircraft and maintain a large enough takeoff queue at the runway. The demand for the departure runway is particularly reduced during Local GS restrictions on the traffic through exit fixes. Such restrictions affect large numbers of aircraft that are stranded on the airport ground.

Figure 6.2 shows graphically how it is possible to meet certain downstream restrictions (particularly non-GS type restrictions) often by a simple reallocation of departure aircraft in the takeoff sequence. If there is enough demand, it is possible to insert the appropriate number of aircraft in between and ahead of the restricted aircraft, resulting in no effect on the queue size or throughput of the system. In order to achieve this the air traffic controllers have to manage the aircraft movement accurately, through controlling the sequence and the time in the system of the restricted aircraft. This control behavior is described next (in the context of the controlled queuing model posed in Chapter 3) under two observed downstream restriction situations: the takeoff time-window control and "splitter" sequencing.
Figure 6.2: Aircraft sequencing under downstream restrictions

6.2.1 Takeoff time window control

The air traffic controllers are often faced with attempting to control the movement of a restricted departure aircraft such that it takes off within an assigned time window (for example the DSP and the EDCT restrictions). In terms of the controlled queuing model posed in Chapter 3, this translates into a desired time \( D_r \) in the system for the restricted aircraft, between the current time and the assigned takeoff time. The air traffic controllers need to allocate the desired time in the system between effective service time \( ES = S + S_p \) and effective waiting time \( EW = W_p + W_{FCFS} \), which they could affect through their control actions as shown in the closed loop control representation in Figure 6.3. As implied in Figure 6.3, observing the queue size (among other information), the air traffic controllers can affect the procedural time component \( (S_p) \) and the queue size (both \( N_{FCFS} \) and \( N_p \)) such that the error between the desired and actual taxi out times is reduced to zero.
Figure 6.3: Closed-loop time window control

As mentioned in Section 3.3, the air traffic controllers can affect the effective service time ($S + S_P$) of the restricted aircraft, mainly by holding the clearances for the procedural time ($S_P$). (They may possibly be able to affect $S$ by asking the aircraft to slow down or speed up, although this is less effective). The time window may then be achieved through proper sequencing (as suggested in Figure 6.2) which may affect the two waiting time components $W_{FCFS}$ and $W_F$. Control of the FCFS waiting time ($W_{FCFS}$) is limited as it entails holding other aircraft already ahead in the system ($N_{FCFS}$) and allowing the restricted aircraft to pass them. Many of these aircraft may be already in the takeoff queue, where there is a limited ability to resequence aircraft (as was shown in Chapter 5). If the desired taxi out time is larger than what it is estimated to be given the queue size, more aircraft ($N_P$) may be allowed to pass the restricted aircraft and be sequenced ahead. However, this should be done with care that the accumulated marginal waiting time caused by each does not lead to a violation of the requested time window.
6.2.2 The “Splitter” sequencing problem

As shown in Figure 6.2, the spacing type restriction (Miles or Minutes in Trail) may be achieved by inserting a number of departure aircraft in between in the takeoff sequence such that the accumulated marginal time due to each makes up the required time spacing. The inserted aircraft is commonly known as a “splitter.” Knowledge of the marginal taxi out time (the slope of the taxi out versus queue size curve) due to each aircraft sequenced ahead in the queue is, therefore, critical for ensuring the required time spacing.

6.3 Effect of uncertainty

Attempting to meet a required takeoff time, especially with a small time window of three minutes as in the case of a DSP restriction, is probably the hardest control problem that the air traffic controllers face in terms of required accuracy. There is a high uncertainty associated with the time that a departure aircraft spends in the system. For example, the standard deviation in the taxi out time between pushback and takeoff (measured by the ASQP data in July 1998) was 10:21 minutes (Figure 4.6). Delcaire and Pujet showed that it is possible to reduce the error in estimating the taxi out time to about 5 minutes if estimated for a specific runway configuration and specific airline (general gate location). Figure 4.7 showed that the standard deviation was about 3 minutes with zero queue size and increased as a function of the queue size. It was also shown in Figure 5.2 that the standard deviation in the runway phase time, between handoff to the
Local controller (the "monitor tower" command) and the takeoff clearance, was 3:48 minutes\textsuperscript{22}. Therefore, even if the air traffic controller waited until the aircraft was about to enter the runway queue, there is still high uncertainty in predicting its takeoff time. This high uncertainty results in a large chance to miss the assigned time window, resulting in non-compliance or forcing a call back for another takeoff time assignment.

The uncertainty also hinders the ability to implement the in-trail requirement. However, usually the in-trail spacing is required between the aircraft as they pass over a downstream fix. Therefore, as observed at Logan Airport, the spacing requirement is less critical than the time window requirement since it can be established in the air after takeoff. In order to achieve higher efficiency by avoiding holding aircraft in the takeoff queue, the Control Tower may coordinate with the TRACON to ensure that the required in-trail spacing is achieved after takeoff.

### 6.3.1 Uncertainty under the DSP restriction case

The Departure Sequencing Program (DSP) is used by the ARTCC (Boston Center in the case of Logan) when there is congestion over an airspace sector under its control. DSP is one manifestation of blocking of an upstream resource (the runway) due to capacity limitations at a downstream resource (the sector). Usually, the ARTCC insures the timely application of the program such that action is taken when certain thresholds rather than the absolute physical capacity limitation is reached. The congested downstream sector is usually fed by traffic from

\textsuperscript{22} The state of information of the air traffic controller is better than what the analysis of either the ASQP or the communication data predict. For example, estimating the system time depends on the runway configuration, the gate location, the weather and airport surface conditions, which the controllers know. It also depends on the state of progress of the aircraft and any problems they encounter, which the controllers may also be able to observe and be informed about through the controller/pilot communication. Therefore, the controllers are probably able to do better predictions and control, especially after the aircraft is on a movement area under their control.
the departure runways of a number of airports. In order to regulate the flow into the sector, aircraft are assigned time slots over certain points, such as the entry fixes into the sector. Aircraft heading to these fixes are then assigned wheels off times by the ARTCC such that they meet their time slots over the fix.

The DSP restriction is implemented as follows: The ARTCC announces to the airport tower that DSP is in effect to a certain destination. When an aircraft that is affected by DSP is on a movement area (under ATC control), the Traffic Management Coordinator (TMC) estimates its wheels off time given the current runway configuration and congestion level on the airport surface. The TMC then calls the ARTCC informing them of the estimated wheels off time, and the ARTCC either approves the estimated time or assigns a different wheels off time in order to meet the assigned slot over the fix. The Control Tower is expected to meet the wheels off time of the aircraft no earlier and at most 3 minutes later than the assigned time. Otherwise the Control Tower has to call the ARTCC back for another wheels off time assignment. Figure 6.4 shows a schematic of the transformation of a DSP time slot at a fix into a DSP wheels-off time window for aircraft A. Aircraft A has to takeoff such that it meets its time slot at the fix.
Figure 6.4: DSP restriction mechanism

Figure 6.5 shows graphically the relationship between the required time of arrival at the fix and the takeoff clearance time at the runway. The profile of aircraft A from the runway to the fix (including the runway occupancy time) is needed in order to compute the 3-minute time window allowed for the wheels-off and hence the takeoff clearance. In practice estimates (based on historic data) of the time that it takes certain types of aircraft to reach the fix from the runway are used for the profile.
Therefore, the problem becomes insuring that the aircraft is at the runway end within the desired 3-minute DSP time window. In order to meet the time window at the runway end there is a desired taxi out time for aircraft A, that the air traffic controllers need to achieve. The aircraft may be held on the gate and on the taxiways to absorb any delay; however, the critical performance cost is in blocking the runway if the aircraft had to be held in the takeoff queue to wait for its required wheels-off time. There are three cases:

- The aircraft arrives at the runway end early relative to its DSP time window. In this case the aircraft has to be held, blocking the runway, until the DSP time. (The existence of a penalty box near the runway end as shown in Figure 6.4 reduces this blocking effect).
- The aircraft arrives at the runway end within the DSP time window and no blocking of the runway occurs.
- The aircraft arrives at the runway end late relative to the DSP time window. In this case a call back to the ARTCC for another DSP time assignment is needed. The runway may be blocked longer depending on the new time and also on the existence of a penalty box.
Given the current position of the aircraft and the current congestion level on the airport surface, there is a range of possible arrival times at the runway end for aircraft A. The three cases above result from the overlap between this range and the required DSP time window. An overlap indicates that it is feasible to meet the DSP time. If the distribution of the arrival time at the runway end is known, it is then possible to determine the probability of meeting the DSP time window or missing it. Figure 6.6 shows a hypothetical distribution of the aircraft arrival time at the runway end, with the DSP time window superimposed. The DSP time window breaks the range into at most three areas, which correspond to the following probabilities:

- The area under the curve within the DSP time window is the probability of meeting the DSP time, without blocking.

- The area under the curve to the left of the DSP time window is the probability that the aircraft is early. The DSP time is met but with blocking (if there is no penalty box).

- The area under the curve to the right of the DSP time window is the probability that the aircraft is late and the DSP time is missed. A call back is needed and excessive blocking may result if there is no penalty box.
6.3.2 A numerical example

Figure 6.7 shows the distribution of the time between the entry into the takeoff queue and the takeoff clearance (measured by the controller's commands of "monitor tower" and "clear for takeoff," respectively), for a sample of eight hours of controller/pilot communication data at Logan (see Chapter 5, Figure 5.2). Given that aircraft A is about to enter the takeoff queue and is faced with the same conditions, the distribution in Figure 6.7 approximates the distribution of its arrival at the runway. One can then estimate the probabilities mentioned above given this distribution.
Figure 6.7: Distribution of arrival time at runway from entry to the takeoff queue

Ignoring the outlier at 24 minutes, the distribution in Figure 6.7 seems to be symmetric. For simplicity, a symmetric triangular distribution with a mean value of 9:30 minutes and a range between 30 seconds and 18:30 minutes is assumed (as shown in Figure 6.8) in order to compute a rough estimate of the probabilities of meeting/missing a time window for takeoff. The DSP 3-minute window is centered at the mean value in order to maximize the probability of meeting the required DSP time. As a result the probability of meeting the DSP time window is only about 0.3 and each of the other two probabilities (late and early arrival) is about 0.35. As mentioned above the early arrival does not imply missing the DSP time window, rather simply possible blocking of the runway in the absence of a penalty box where the delay can be absorbed.
Figure 6.8: Numerical example using a triangular distribution

One reason for the high uncertainty in the arrival time at the runway end is the variation in the number of aircraft in the takeoff queue. Since this number is observable however, to the controller for example, the uncertainty should be less given knowledge of the number of aircraft ahead in the takeoff queue. Figure 6.9 shows for the sample of the eight hours of communication data, the distribution of the size of the takeoff queue, along with the average and the standard deviation of the waiting time as a function of the queue size. While the average time in the takeoff queue clearly increases with the queue size, the standard deviation seems to be more constant at about 2 minutes, increasing to about 3 minutes for queues larger than 10 aircraft. Assuming that the uncertainty in the arrival time at the runway is reduced from about 3 to about 2 minutes with knowledge of the queue size, the probability of blocking the queue because of a DSP restriction is reduced slightly from the example above.
Figure 6.9: Queuing dynamics of the runway phase

**Note 1:** Given certain costs associated with runway blocking, delay, and non-compliance with the DSP slot downstream, an optimal location of the DSP 3-minute time window relative to the distribution of the arrival time at the runway may be computed.

**Note 2:** If a penalty box exists at the runway end, with enough capacity, restricted aircraft can wait away from the flow stream in both the early and late arrival cases. The only cost in this case is the one associated with the delay to the aircraft itself, and non-compliance with the slot over the fix. In addition, in the absence of dedicated penalty boxes at the runway end, the entry into the takeoff queue is the last control point that dictates the sequence of the aircraft in the takeoff queue. After this point the aircraft is in a single queue, single runway system (as was observed in Figure 5.2). Any holding of the aircraft then causes blocking of the runway and loss of
efficiency. Therefore, dedicated penalty boxes next to the runway ends ensure better compliance with restrictions and higher efficiency.

**Note 3:** Before the aircraft is on a movement area, it is even more difficult for the controllers to predict the takeoff time due to the lack of observability of the aircraft state on the gate and the high uncertainty associated with the gate operations. In (Idris) it was shown that there is a large variability (14 minute standard deviation) in the time between the proposed pushback time and the time the aircraft calls ready for pushback (or ready for taxi if non-jet). It would be extremely difficult for an air traffic controller to predict the pushback time accurately based on the proposed schedule time. This explains waiting until the aircraft is on a movement area before the Traffic Management Coordinator (TMC) predicts the takeoff time and calls the Boston Center (ATRCC) asking for a DSP time assignment. Holding on the gate, which might be beneficial for airlines and for the airport congestion and environment, is precluded in such cases. On the other hand, the 15-minute time window for the EDCT restriction allows for a larger margin for error.
Chapter 7
Conclusions

7.1 Summary

In this thesis a model of the departure process at an airport system was developed, which represents the queuing dynamics and the tactical control behavior. The control behavior was manifested mainly by passing, which results from sequencing of aircraft and their suspension under special circumstances such as downstream restrictions.

The model was applied to the overall departure process between pushback and takeoff (as measured by the ASQP data) for the month of July 1998 at Logan Airport. The time that a departure aircraft spent in the process was analyzed. It was found that a departure aircraft spent an average unimpeded free-flow time of about 11:40 minutes, which may have included procedural interruptions by the air traffic controllers. In addition the aircraft spent a waiting time due to queuing, which was mainly due to a dominant FCFS behavior. A low level of passing was observed (an average of 0.8 aircraft passed and were passed by another aircraft) while the total queue that an aircraft experienced had an average length of 5.6 aircraft.

Each aircraft in the queue caused an average marginal waiting time of about 1.8 minutes, although this marginal time was a function of the queue size. The marginal waiting time per passing aircraft (aircraft that passed the affected aircraft during its taxi out) was higher than the average, which indicated that the affected passed aircraft were in some cases suspended for long
periods of time that included idle runway periods. This was evident from the analysis of the time in the system for aircraft under downstream restrictions. Aircraft that suffered a Ground Stop restriction seemed to spend more time in the system than other restricted aircraft and accounted for most of the excessive passing. On the other hand aircraft that were restricted by a takeoff time window or a takeoff spacing type restrictions followed the nominal queuing behavior, indicating that there was often no need to suspend such restricted aircraft. In these cases the restriction could be complied with simply by sequencing aircraft in the appropriate order such that they arrive at the runway at their desired time.

It was observed that the level of sequencing, and therefore control, was moderate at Logan airport (only 0.8 aircraft passed or were passed by another aircraft on average). This is explained by the constrained geometry and the lack of real estate at the airport and the use of a single departure runway most of the time. From the comparison of the dynamics in four departure sub-processes (runway, taxi, ramp and pre-pushback) defined between controller/pilot communication events, it was observed that the control opportunity decreased in the runway phase after aircraft joined the takeoff queue. It was also observed that aircraft incurred most of their delay in the takeoff queue, where the time in the runway phase averaged 9:40 minutes, more than twice the average time spent in the preceding phases.

A high level of uncertainty was observed in the taxi out time. Although no effort was made in this thesis to account for all the factors that cause variation in the taxi out time, it was evident that the variability was a function of the queue size. Knowledge about the passing behavior and therefore, predicting the actual queue size from an observed queue size at pushback would therefore reduce the uncertainty in taxi out time estimation. The uncertainty is a major factor that hinders the air traffic controllers' ability to control the taxi out time and comply with certain
restrictions, particularly the takeoff time-window type restriction. It was shown that there is a high probability to miss the DSP 3-minute takeoff time window restriction, even if the controller waited until the aircraft is at the entry to the takeoff queue to insert it in the appropriate sequence. This is caused by the variability in the time spent in the runway phase between entry into the takeoff queue ("monitor tower" instruction) and the takeoff clearance (ranges between 2 to 3 minutes depending on the queue size). With the lack of a penalty box near the runway end, an early or late arrival of an aircraft would cause blocking of the runway and loss of efficiency in addition to the incurred delays.

7.2 Implications

When the ability to sequence aircraft is limited such as at Logan airport, and the uncertainty in the taxi out dynamics is high, it is extremely difficult to comply with restrictions on the takeoff time without blocking the runways. The result is either a loss of efficiency or a high rate of non-compliance. Departure planning may help improve the system performance with better information and more accurate modeling and prediction that would reduce the uncertainty. For example, it is essential to know the marginal time that each aircraft in the queue causes, in order to decide on the queue size in front of a restricted aircraft that needs to be at the runway at a particular time. Due to the high uncertainty in the departure process dynamics, the air traffic controllers currently have little hope to start sequencing the aircraft prior to pushback or even during the early stages of taxiing. Instead restricted aircraft are expedited to the runway end and if early are held in penalty boxes when they exist. This reduces the ability to absorb delays on the gates (which is less costly and more convenient) and results in blocking of the runway in the absence of penalty boxes.
Therefore, models of the tactical queuing and control behavior such as the one developed in this thesis should be helpful in assisting tactical control tools for departure planning. Such models should be developed for specific runway configurations, and take into account factors that affect the runway capacity such as arrival aircraft, runway crossings and the controller workload.

7.3 Future work

Based on the analytical model posed in this thesis, statistical models can be developed by estimating the queuing parameters such as the effective (free-flow) service time, marginal system time and system capacity. This should be done under specific environmental conditions such as weather and runway configuration. Taking the passing behavior and downstream restrictions into account should improve the accuracy of the estimated models.

Then such models can be used to test different control strategies, for the Departure Planner tools or other improved methods. The model in this thesis represents the core, tactical-level queuing and control behavior. At this level the main goal is to comply with higher-level control strategies such as sequencing, restrictions and flow control. Sequencing may be needed for efficient runway operations in order to insert departures in the appropriate time slots within an arrival stream, or in order to takeoff in an assigned time window imposed by a restriction without blocking the runway. Flow control may be needed in order to regulate the flow outbound from the airport at a rate that matches the capacity of downstream locations of the NAS. At the tactical level, these higher-level control strategies are transformed into a desired time in the system for each aircraft in the departure process. The time in the system may start at the pushback, earlier or later, depending on the time horizon that defines the system. The time in the system then needs to be controlled appropriately to achieve a required takeoff time, a sequence, a
desired queue size or a desired departure flow rate. For example, control strategies for the time in the system may be designed in order to maximize the probability of meeting (or minimize the probability of missing) the desired takeoff time window. This time control problem is the core tactical control task that would help implement any higher-level departure flow management strategy.
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