

**STRATEGIC DECISION SUPPORT FOR AIRPORT CAPACITY PLANNING**

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AN APPLICATION OF

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# **DISCRETE EVENT SIMULATION IN A STAGED QUEUEING FRAMEWORK FOR AIRSIDE OPERATIONS**

**Final Report  
April 2018**

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# **STRATEGIC DECISION SUPPORT FOR AIRPORT CAPACITY PLANNING: AN APPLICATION OF DISCRETE EVENT SIMULATION IN A STAGED QUEUEING FRAMEWORK FOR AIRSIDE OPERATIONS**

**Final Report  
April 2018**

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## TABLE OF CONTENTS

ACKNOWLEDGMENTS .....	ix
INTRODUCTION .....	1
REPRESENTATION OF THE STAGED QUEUEING FRAMEWORK .....	3
Taxi Routes .....	6
DATA FOR MODEL CALIBRATION .....	13
HISTORICAL ANALYSIS OF FLIGHT OPERATIONS.....	14
IMPOSING VARIATION IN ARRIVAL AND TURNAROUND TIMES .....	16
USE OF THE SIMULATION MODEL FOR STRATEGIC ANALYSIS .....	22
MODEL CALIBRATION AND VALIDATION.....	24
DEFINING SCENARIOS IN THE ARENA MODEL FOR STRATEGIC ANALYSIS .....	34
Altering Flight Schedules (Especially to Increase Traffic Levels).....	34
Changing Runway Usage.....	35
Changing Tractor Availability, Preferences, and Range of Activity .....	36
Changing Capacities in Airport Infrastructure.....	37
Limiting Traffic in Hotspots .....	37
Assigning Alternative Parking Sections When No Spot is Available in the Preferred Section as a Plane Arrives (for Advanced Users).....	37
Changing ATC Rules for Handling Traffic (for Advanced Users).....	38
Imposing Gate Holds as a Flight Flow-Control Mechanism .....	39
SUMMARY OF USER-ADJUSTABLE PARAMETERS .....	41
SAMPLE INSIGHTS FROM SIMULATION RESULTS .....	42
Historical Delays and Taxi Times.....	43
Deployment of Tractors for Pushbacks.....	43
ATC Separation Standards for Approaches and Departures.....	44
Runway Usage .....	44
STEPS FOR RUNNING THE ARENA SIMULATION MODEL AND SAS REPORT GENERATOR .....	46
CONCLUSION.....	48
REFERENCES .....	49
APPENDIX A. USER-DEFINED VARIABLES AND EXPRESSIONS.....	51
APPENDIX B. RESULTS OF APPLYING THE SIMULATION MODEL.....	57

## LIST OF FIGURES

Figure 1. Domain of airside operations.....	2
Figure 2. Sample airport diagram with parking sections .....	3
Figure 3. Excerpt from initial states.....	15
Figure 4. Residual variation in pushback delays relative to scheduled departure time .....	20
Figure 5. Hourly activities if all operations occur exactly according to the day’s schedule .....	26
Figure 6. Actual hourly activities.....	27
Figure 7. Simulated hourly activities in one replication .....	28
Figure 8. Hourly activity in 100 replications of the daily schedule.....	29
Figure 9. Actual delay and taxi times for chosen day.....	30
Figure 10. Simulated activity for one day with AOC-assigned gates used to indicate preferred parking sections .....	31
Figure 11. Simulated activity for 100 days with AOC-assigned gates used to indicate preferred parking sections .....	32
Figure 12. Process blocks for crossing ramp in Parking Section 1.....	33
Figure 13. Animated performance dashboards for tractor usage and gate activity .....	34
Figure 14. Dashboard for ATC runway usage .....	35
Figure 15. Queue animated in-process flow .....	35
Figure 16. Changing tractor availability, preferences, and range of activity.....	36
Figure 17. Altering priorities for traffic handling.....	39
Figure 18. Checking status of airport operations and placing holds on aircraft pushback .....	39
Figure 19. Module regulating outbound release of aircraft .....	40
Figure 20. Scheduled daily flight activity.....	42
Figure 21. Pushback delays while waiting for tractors: with original tractor deployment (left) and with adjusted tractor deployment (right) .....	44
Figure 22. Run wedge button.....	46
Figure 23. Stop Run button.....	46
Figure 24. Stopping to examine the dashboard at a particular time of day .....	46
Figure 25. Animated status of queues.....	47
Figure B.1. Simulated performance statistics base case, 100 replications, landing RWY 25 and departing RWY 24.....	57
Figure B.2. Simulated performance statistics base case, 100 replications, landing RWY 24 and departing RWY 25.....	58
Figure B.3. Simulated performance statistics base case, 100 replications, landing RWY 24 and departing RWY 24 and RWY 25 .....	59



## LIST OF TABLES

Table 1. Aircraft parking sections.....	4
Table 2. Average simulated taxi times by parking section when landing on RWY 07 and taking off from RWY 06 using STL midweek flight schedule.....	10
Table 3. Average simulated taxi times by parking section when landing on RWY 06 and taking off from RWY 07 using STL midweek flight schedule.....	10
Table 4. Average simulated taxi times by parking section when landing on RWY 24 and taking off from RWY 25 using STL midweek flight schedule.....	11
Table 5. Average simulated taxi times by parking section when landing on RWY 25 and taking off from RWY 24 using STL midweek flight schedule.....	11
Table 6. Primary experimental factors.....	22
Table A.1. Variables used to create simulation scenarios or employed in the embedded statistical models.....	51
Table A.2. User-defined expressions for controlling process flow.....	53
Table A.3. Other variables used in model logic (not controlled exogenously).....	56



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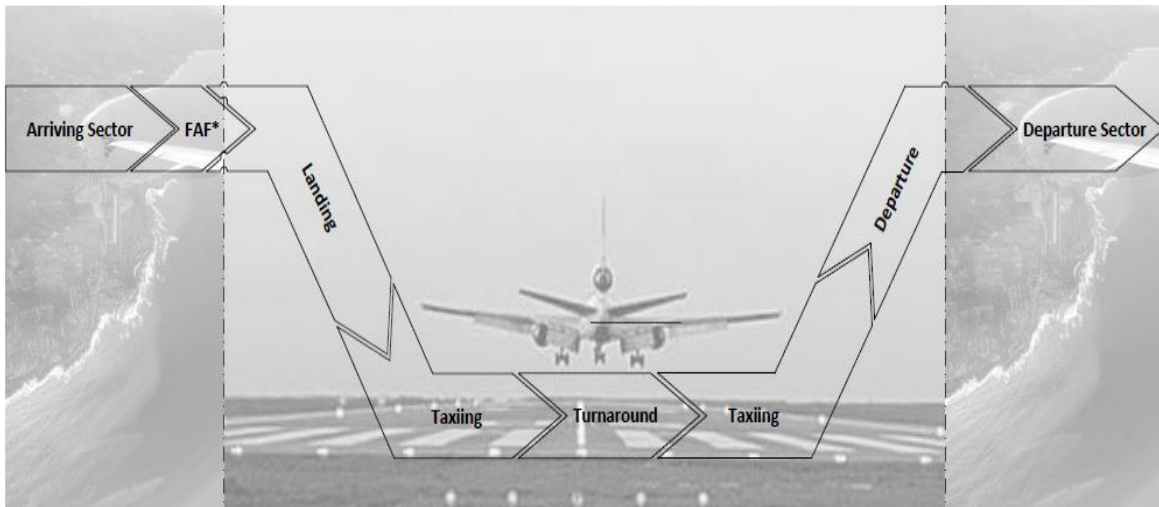
## INTRODUCTION

Airside performance is affected by a large number of interacting factors in three major spheres of airside activity: (1) airport operations control (AOC), (2) maintenance services, and (3) air traffic control (ATC). The AOC is responsible for the assignment of preferred parking sections (with associated terminal gates). It is also responsible for sending planes to alternative parking spots when there is not a gate available in the preferred section for an arriving aircraft. Maintenance personnel provide turnaround services and deploy tractors for pushbacks at gates and for airlines that require such service. ATC determines how runways are used for arrivals and departures according to wind conditions and coordinates aircraft traffic for safe operation. Smooth operation requires close cooperation among these three spheres of activity. In this report, the researchers describe a discrete-event simulation model and supporting analytical tools designed to help airport planners, operations directors, and air traffic control specialists collaborate in maximizing airside performance.

With information provided from the model and supplemental statistical analysis, these parties can objectively address strategic questions such as the following:

- What are the key constraints in accommodating future growth in traffic?
- What is the consequence of changing scheduled arrivals and departures (shifting scheduled arrival and departure times for existing flights or adding new flights)?
- What operational changes provide opportunities to increase the efficiency of airside operations?
- What is the consequence of changing how runways are used for arrivals and departures?
- How does performance depend on the positioning and range of activity of tractors used to push back aircraft that are parked at gates or parking stands that require such service?
- How does performance depend on the assignment of preferred parking sections to individual flights and on rules for selecting alternative parking sections if no spots are available in the preferred parking section when an aircraft arrives?
- What are the potential effects of changes to physical infrastructure (taxiways, runways, ramps [aprons], staging areas)?

The simulation model for airside operations was originally developed in collaboration with the St. Louis Lambert International Airport (STL) (Smith et al. 2014, Smith et al. 2015, Smith et al. 2017). It represents activity from the time when aircraft reach local airspace, through final approach, touchdown on the runway, taxiing to parking areas, turnaround activity before departure, taxiing to the departure runway, and takeoff for the departing flight. Figure 1 illustrates the problem domain. The model is designed to incorporate critical aspects of airside activity without unnecessary granularity. The conceptual framework of the model involves process flow in staged queues. The model has parameters that allow changes to infrastructure and operations in each of the three spheres of operation.

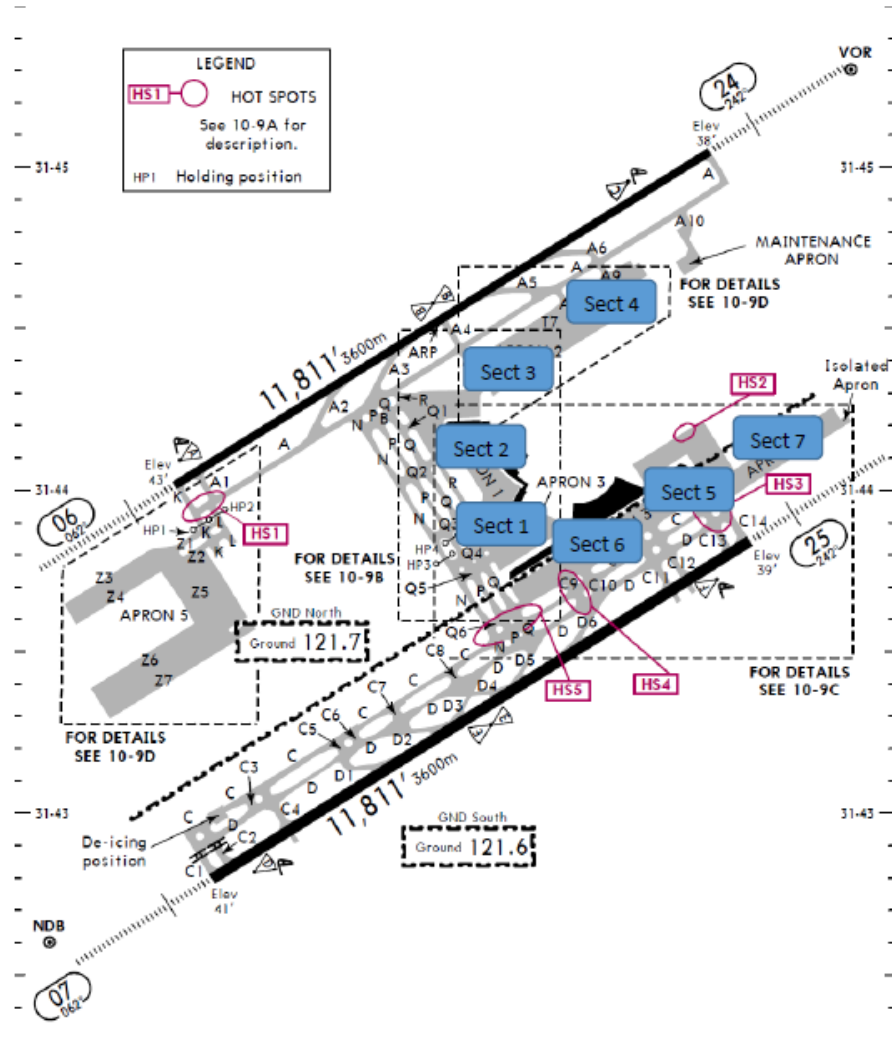


**Figure 1. Domain of airside operations**

In this phase of research on decision support for airport asset management, the researchers create performance dashboards that help analysts configure assets and deploy them effectively, and include additional features for representing flow control in the air and on the ground by ATC. Ground support equipment (tractors) deployed by AOC as a service to airlines are also included. With an enriched (and confidential) database that matched individual aircraft with scheduled flights, statistical models were created for representing arrival delays and elements of turnaround time on the ground for individual aircraft based on their inbound and outbound flight schedules. Such models allow information to be conveyed to individual airlines about the effects of schedule changes upon their own airside performance and on the performance of others that share the same airport resources. Finally, the researchers consider how the simulation model may be used to identify key constraints on airside operations and facilitate cooperation among parties as they collaborate to maximize airside performance in a specific setting.

## REPRESENTATION OF THE STAGED QUEUEING FRAMEWORK

Aircraft movements on the ground at commercial airports occur through a networks of taxiways such as those depicted on the airport diagram in Figure 2.



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**Figure 2. Sample airport diagram with parking sections**

The basic layout of the airport is fixed as a template in an Arena 14.7 model. This template was derived (with permission) from the Jeppesen Sanderson airport diagram used by pilots. Lengths of taxiway segments were estimated by using calipers and ratios of measured lengths relative to the longest runway (with stipulated length in feet) on the airport diagram. For the staged queueing representation of aircraft movements, aircraft parking locations (gates) were grouped into main sections with common points of ingress and egress to ramp areas (aprons) at passenger terminals or at remote parking stands served by busses. For each section, there is a staging point for arrivals (with designated capacity) and a staging point for departures. In the illustrative case,

there are seven parking areas for commercial flights and another area without designated gates for air cargo operations.

Simulation of airside activity involved the following elements:

- Generating arrivals in local airspace according to schedule with random variation in arrival times relative to scheduled arrival times (and possible delays to represent disruptions due to weather or traffic delays at the previous airport). Aircraft were queued at the final approach fix for the assigned runway and released for approach with consideration of separation standards for flight safety.
- Execution of the approach and touchdown and clearance on the runway.
- Assignment of parking position to be used.
- Movement along designated taxi routes to the staging point for arrivals to the designated parking area.
- Movement across ramps (aprons) to the designated parking position when the specific parking position was vacant.
- Completion of ground services and preparation of the airplane for departure.
- Pushback of the aircraft and movement across a ramp to the staging point for departures.
- Movement along designated taxi routes to the runway assigned for departure.
- Queueing at staging points, taxiway intersections, and the runway for departure.
- Release of aircraft for takeoff and departure with appropriate separation for safety.

In the simulation model, the researchers referred to all parking locations as gates regardless of whether they had passenger bridges to the terminal or required busing of passengers from the tarmac. Gates associated with each of the seven parking sections for passenger activity are included in Table 1.

**Table 1. Aircraft parking sections**

<b>Section</b>	<b>Designated Parking Spots</b>	<b>T1 Spots</b>	<b>T2 Spots</b>	<b>Associated Gates (or Parking Stands)</b>
<b>1</b>	10	10	0	Gates 101-110
<b>2</b>	12	12	0	Gates 201-212
<b>3</b>	15	15	0	Gates 301-315
<b>4</b>	8	8	0	Gates 401-408
<b>5</b>	21	0	21	Gates 501-521
<b>6</b>	20	0	20	Gates 601-620
<b>7</b>	11	0	11	Gates 701-711
<b>8</b>	0	0	0	Apron 5 Cargo Ramp
<b>9</b>	0	0	0	TBA
<b>Total</b>	97	45	52	



Taxiways and runways were represented as resources with limited capacity and directional control. Intersections and gates were represented as resources with complementary stations. Aircraft were “routed” from station to station with designated taxi speeds along fixed taxiway routes for inbound and outbound flights, depending on the parking section and runway to be used. The taxi routes share common resources such as ramps (aprons), taxiway segments, intersections, and staging pads on the airport surface. Other resources included individual gates, runways, airspace for holding aircraft outside the final approach fix, and airspace occupied by airplanes on short final approaches for the four individual runways (RWYS 24, 25, 06, and 07). Some resources had a capacity of one aircraft (runways, gates, short final approaches, intersections); others such as staging pads and taxiways were allowed to accommodate several aircraft (which could be maneuvered as directed by ATC ground control with some additional flexibility).

Resources were “seized” with stipulated priority by an aircraft and were released as they moved to the next stage of their scheduled activity. Gates were expanded or contracted in a section (without detailed animation) simply by increasing or decreasing the capacity of individual gates (measured by the number of aircraft they could accommodate).

Directional controls on runways and taxiways often depended on what runways were active for departure and landing. The layout of the illustrative airport made natural use of RWY 24 for landings and RWY 25 for departures when winds were from the southwest. When winds were from the northeast, the natural use would be RWY 07 for landings and RWY 06 for departures. These usages would be expected to result in the lowest average taxi times overall if ATC wished to use one runway exclusively for landings and another for departures. It was also possible to interleaf arrivals and departures on a runway with consideration of the aircraft’s parking location to reduce inbound and outbound taxi times. The simulation model may be used to test such options.

The simulation model may also be run with animation that illustrates the status of the airport at any point in simulated time. It shows movements of aircraft on the airfield and presents statistics that show the cumulative number of arrivals and departures for each of the runways in the simulated time frame (usually one day, beginning at midnight). It may also be run in batch mode to produce detailed event logs of simulated activity for many replications of the chosen schedule. Those logs are analyzed externally (using a SAS or Statistical Analysis System) to produce comprehensive reports with simulation details and performance summaries at several dimensions.

As mentioned earlier, the simulation model represents activity for which three main departments bear responsibility:

1. AOC: Determines the gates to be used by arriving aircraft considering their scheduled arrival and departure times and other relevant factors such as whether the arriving or departing flight is domestic or international, size of aircraft, and airline involved.
2. Maintenance: Provides ground support for servicing aircraft and pushing them back with tractors for departure.

3. ATC: Determines what runway is to be used for each arrival and departure and directs movements of aircraft on the ground and in nearby airspace.

The animated version of the model has performance dashboards that provide critical information for each of these spheres of operation. The animated dashboards enable a user of the model to verify that the simulated activity is appropriate for the chosen scenario and to adjust resources and operating rules to produce a sustainable level of activity.

After a sustainable configuration is achieved, multiple replications of a daily schedule may be run in batch mode to enable comprehensive statistical analysis that distinguishes random versus systematic variation associated with performance measures from different simulation scenarios.

Taxiway segments and intersections are designated for each possible combination of runway (RWY 24, 25, 06, or 07) and parking sections (1 through 7). The 28 resulting combinations for default taxi routes are as follows:

### **Taxi Routes**

Landing 24 (runway index = 1)

Clear RWY 24 at A3Pint and taxi as follows:

- For Section 1 (Gates 1–4, 16–21) via Nnorth → Ncenter → NQ3int → Q3 → Sect1arr
- For Section 2 (Gates 5–10, 13–15, 32–34) via Nnorth → NQ2int → Q2 → Sect2arr
- For Section 3 (Gates 51–65) via Acenterwest → A7 → Sect3arr
- For Section 4 (Gates 66–73) via Acenterwest → Acentereast → A8 → Sect4arr
- For Section 5 (Gates 201–212, 260–268) via Nnorth → Ncenter → Nsouth → NQ6int → DNint → DQint → Deast → C12 → Sect5arr
- For Section 6 (Gates 213–232) via Nnorth → Ncenter → Nsouth → NQ6int → DNint → DQint → Deast → C10 → Sect6arr
- For Section 7 (Gates 269–279) via Nnorth → Ncenter → Nsouth → NQ6int → DNint → DQint → Deast → C14 → Sect7arr

Landing 25 (runway index = 2)

Clear RWY 25 at D4C8int and taxi as follows:

- For Section 1 (Gates 1–4, 16–21) via Dwest → DQint → Qsouth → QQ3int → Q3 → Sect1arr
- For Section 2 (Gates 5–10, 13–15, 32–34) via Dwest → DQint → Qsouth → Qcenter → QQ2int → Q2 → Sect2arr
- For Section 3 (Gates 51–65) via Dwest → DQint → Qsouth → Qcenter → Qnorth → A3Pint → Acenterwest → A7 → Sect3arr

- For Section 4 (Gates 66–73) via Dwest → DQint → Qsouth → Qcenter → Qnorth → A3Pint → Acenterwest → Acentereast → A8 → Sect4arr
- For Section 5 (Gates 201–212, 260–268) via Dwest → DNint → DQint → Deast → C12 → Sect5arr
- For Section 6 (Gates 213–232) via Dwest → DNint → DQint → Deast → C10 → Sect6arr
- For Section 7 (Gates 269–279) via Dwest → DNint → DQint → Deast → C14 → Sect7arr

Landing 06 (runway index = 3)

Clear RWY 06 via A5 to A5A8int and taxi as follows:

- For Section 1 (Gates 1–4, 16–21) via Acentereast → Acenterwest → A3Pint → Nnorth → Ncenter → NQ3int → Q3 → Sect1arr
- For Section 2 (Gates 5–10, 13–15, 32–34) via Acentereast → Acenterwest → A3Pint → Nnorth → NQ2int → Q2 → Sect2arr
- For Section 3 (Gates 51–65) via Acentereast → A7 → Sect3arr
- For Section 4 (Gates 66–73) via Acentereast → A8 → Sect4arr
- For Section 5 (Gates 201–212, 260–268) via Acentereast → Acenterwest → A3Pint → Nnorth → Ncenter → Nsouth → NQ6int → DNint → DQint → Deast → C12 → Sect5arr
- For Section 6 (Gates 213–232) via Acentereast → Acenterwest → A3Pint → Nnorth → Ncenter → Nsouth → NQ6int → DNint → DQint → Deast → C10 → Sect6arr
- For Section 7 (Gates 269–279) via Acentereast → Acenterwest → A3Pint → Nnorth → Ncenter → Nsouth → NQ6int → DNint → DQint → Deast → C14 → Sect7arr

Landing 07 (runway index = 4)

Clear RWY 07 via D5 to D5Qint and taxi as follows:

- For Section 1 (Gates 1–4, 16–21) via DQint → Qsouth → QQ3int → Q3 → Sect1arr
- For Section 2 (Gates 5–10, 13–15, 32–34) via DQint → Qsouth → Qcenter → QQ2int → Q2 → Sect2arr
- For Section 3 (Gates 51–65) via DQint → Qsouth → Qcenter → Qnorth → A3Pint → Acenterwest → A7 → Sect3arr
- For Section 4 (Gates 66–73) via DQint → Qsouth → Qcenter → Qnorth → A3Pint → Acenterwest → Acentereast → A8 → Sect4arr
- For Section 5 (Gates 201–212, 260–268) via DQint → Deast → C12 → Sect5arr
- For Section 6 (Gates 213–232) via DQint → Deast → C10 → Sect6arr
- For Section 7 (Gates 269–279) via DQint → Deast → C14 → Sect7arr

Takeoff 24 (runway index = 1)

- For Section 1 (Gates 1–4, 16–21) via Sect1dep → Q3 → PQ3int → Pcenter → Pnorth → A3Pint → Acenterwest → AA4int → Acentereast → AA6int → Aeast → AAint → 24deppt → ready24
- For Section 2 (Gates 5–10, 13–15, 32–34) via Sect2dep → Q2 → PQ2int → Pnorth → A3Pint → Acenterwest → AA4int → Acentereast → AA6int → Aeast → AAint → 24deppt → ready24
- For Section 3 (Gates 51–65) via Sect3dep → AA4int → Acentereast → AA6int → Aeast → AAint → 24deppt → ready24
- For Section 4 (Gates 66–73) via Sect4dep → AA6int → Aeast → AAint → 24deppt → ready24
- For Section 5 (Gates 201–212, 260–268) via Sect5dep → C11 → Ceast → CPint → Psouth → Pcenter → Pnorth → A3Pint → Acenterwest → AA4int → Acentereast → AA6int → Aeast → AAint → 24deppt → ready24
- For Section 6 (Gates 213–232) via Sect6dep → C9 → Ceast → CPint → Psouth → Pcenter → Pnorth → A3Pint → Acenterwest → AA4int → Acentereast → AA6int → Aeast → AAint → 24deppt → ready24
- For Section 7 (Gates 269–279) via Sect7dep → C13 → Ceast → CPint → Psouth → Pcenter → Pnorth → A3Pint → Acenterwest → AA4int → Acentereast → AA6int → Aeast → AAint → 24deppt → ready24

Takeoff 25 (runway index = 2)

- For Section 1 (Gates 1–4, 16–21) via Sect1dep → Q3 → PQ3int → Nsouth → CPint → Deast → C13Dint → 25deppt → ready25
- For Section 2 (Gates 5–10, 13–15, 32–34) via Sect2dep → Q2 → PQ2int → Ncenter → Nsouth → CPint → Deast → C13Dint → 25deppt → ready25
- For Section 3 (Gates 51–65) via Sect3dep → A7 → AA4int → Acenterwest → APint → Nnorth → Ncenter → Nsouth → CPint → Deast → C13Dint → 25deppt → ready25
- For Section 4 (Gates 66–73) via Sect4dep → A9 → AA6int → Acentereast → AA4int → Acenterwest → APint → Nnorth → Ncenter → Nsouth → CPint → Deast → C13Dint → 25deppt → ready25
- For Section 5 (Gates 201–212, 260–268) via Sect5dep → C11 → Deast → C13Dint → 25deppt → ready25
- For Section 6 (Gates 213–232) via Sect6dep → C9 → Deast → C13Dint → 25deppt → ready25
- For Section 7 (Gates 269–279) via Sect7dep → C13 → Deast → C13Dint → 25deppt → ready25

Takeoff 06 (runway index = 3)

- For Section 1 (Gates 1–4, 16–21) via Sect1dep → Q3 → PQ3int → Pcenter → Pnorth → A3Pint → Awest → AAint → 06deppt → ready06
- For Section 2 (Gates 5–10, 13–15, 32–34) via Sect2dep → Q2 → PQ2int → Pnorth → A3Pint → Awest → AAint → 06deppt → ready06

- For Section 3 (Gates 51–65) via Sect3dep → A7 → AA4int → Acenterwest → A3Pint → Awest → AAint → 06deppt → ready06
- For Section 4 (Gates 66–73) via Sect4dep → A9 → AA6int → Acentereast → AA4int → Acenterwest → A3Pint → Awest → AAint → 06deppt → ready06
- For Section 5 (Gates 201–212, 260–268) via Sect5dep → C11 → Ceast → CPint → Psouth → Pcenter → Pnorth → A3Pint → Awest → AAint → 06deppt → ready06
- For Section 6 (Gates 213–232) via Sect6dep → C9 → Ceast → CPint → Psouth → Pcenter → Pnorth → A3Pint → Awest → AAint → 06deppt → ready06
- For Section 7 (Gates 269–279) via Sect7dep → C13 → Ceast → CPint → Psouth → Pcenter → Pnorth → A3Pint → Awest → AAint → 06deppt → ready06

Takeoff 07 (runway index = 4)

- For Section 1 (Gates 1–4, 16–21) via Sect1dep → Q3 → PQ3int → Nsouth → CPint → Cwest → CC1int → 07deppt → ready07
- For Section 2 (Gates 5–10, 13–15, 32–34) via Sect2dep → Q2 → PQ2int → Ncenter → Nsouth → CPint → Cwest → CC1int → 07deppt → ready07
- For Section 3 (Gates 51–65) via Sect3dep → A7 → AA4int → Acenterwest → APint → Nnorth → Ncenter → Nsouth → CPint → Cwest → CC1int → 07deppt → ready07
- For Section 4 (Gates 66–73) ) via Sect4dep → A9 → AA6int → Acentereast → AA4int → Acenterwest → APint → Nnorth → Ncenter → Nsouth → CPint → Cwest → CC1int → 07deppt → ready07
- For Section 5 (Gates 201–212, 260–268) via Sect5dep → C11 → Ceast → CPint → Cwest → CC1int → 07deppt → ready07
- For Section 6 (Gates 213–232) via Sect6dep → C9 → Ceast → CPint → Cwest → CC1int → 07deppt → ready07
- For Section 7 (Gates 269–279) via Sect7dep → C13 → Ceast → CPint → Cwest → CC1int → 07deppt → ready07

The model considers the distance on each taxiway segment, taxi speed for aircraft, and time involved in crossing some intersections and ramp areas. These, and the waiting times for related resources (or ATC clearance delays for traffic flows in airspace sectors or at specific airports), contribute to inbound and outbound taxi times for individual flights.

Taxi times on taxiway segments are determined by the length of the segments (in feet) divided by the taxi speed in feet/second. Of course, ATC ground controllers may have aircraft use different taxi routes according to specific conditions, but the relative taxi distances and taxi times between parking sections and runways should be represented quite well by these taxi routes.

In the initial development of the model, the researchers simulated performance using data from St. Louis Lambert International Airport and distributed gate activity for the major airlines among the aforementioned parking areas. The model was then run to produce summaries of times spent taxiing in (from touchdown on the runway to arrival at the gate) and taxiing out (from pushback to liftoff, including time for the pushback). This was done for four combinations of runway

usage. Since the traffic volumes were well within the capacity limits, the resulting average taxi times should have been close to unencumbered taxi times for the respective taxi routings. Results are presented in Tables 2 through 5.

**Table 2. Average simulated taxi times by parking section when landing on RWY 07 and taking off from RWY 06 using STL midweek flight schedule**

<b>Parking Section</b>	<b>Number Inbound</b>	<b>Av. Taxi-in Time (min.)</b>	<b>Number Outbound</b>	<b>Av. Taxi-out Time (min.)</b>
<b>1</b>	14	4.9	14	11.9
<b>2</b>	25	5.9	25	10.3
<b>3</b>	19	8.3	16	10.8
<b>4</b>	33	10.3	33	13.2
<b>5</b>	31	5.9	39	15.3
<b>6</b>	26	4.9	26	14.2
<b>7</b>	62	7.1	56	16.5
<b>All Sections</b>	210	7.0	209	14.0

**Table 3. Average simulated taxi times by parking section when landing on RWY 06 and taking off from RWY 07 using STL midweek flight schedule**

<b>Parking Section</b>	<b>Number Inbound</b>	<b>Av. Taxi-in Time (min.)</b>	<b>Number Outbound</b>	<b>Av. Taxi-out Time (min.)</b>
<b>1</b>	14	9.0	14	14.4
<b>2</b>	25	8.0	25	15.6
<b>3</b>	19	5.3	16	17.1
<b>4</b>	33	4.5	33	19.1
<b>5</b>	44	13.5	40	14.1
<b>6</b>	26	12.2	26	13.2
<b>7</b>	49	14.9	55	15.1
<b>All Sections</b>	210	10.5	209	15.5

**Table 4. Average simulated taxi times by parking section when landing on RWY 24 and taking off from RWY 25 using STL midweek flight schedule**

<b>Parking Section</b>	<b>Number Inbound</b>	<b>Av. Taxi-in Time (min.)</b>	<b>Number Outbound</b>	<b>Av. Taxi-out Time (min.)</b>
<b>1</b>	14	5.9	14	15.3
<b>2</b>	25	7.0	25	13.7
<b>3</b>	19	9.4	16	10.5
<b>4</b>	33	11.9	33	8.5
<b>5</b>	41	7.0	46	19.2
<b>6</b>	26	6.0	26	17.7
<b>7</b>	52	8.2	49	19.9
<b>All Sections</b>	210	8.1	209	15.9

**Table 5. Average simulated taxi times by parking section when landing on RWY 25 and taking off from RWY 24 using STL midweek flight schedule**

<b>Parking Section</b>	<b>Number Inbound</b>	<b>Av. Taxi-in Time (min.)</b>	<b>Number Outbound</b>	<b>Av. Taxi-out Time (min.)</b>
<b>1</b>	14	6.2	14	13.2
<b>2</b>	25	5.3	25	13.7
<b>3</b>	19	5.2	16	15.4
<b>4</b>	33	7.2	33	18.0
<b>5</b>	43	10.6	52	7.9
<b>6</b>	26	9.4	26	9.4
<b>7</b>	50	11.9	43	7.1
<b>All Sections</b>	210	8.8	209	11.2

The results were consistent with expectations that landing RWY 24 and departing RWY 25 would minimize overall taxi times when the wind was from the southwest, and landing RWY 07 and departing RWY 06 would minimize taxi times when the wind was from the northeast. This was reinforced when data from the new experimental setting were used to calibrate the model.

The taxi times between parking sections and runways are determined by the cumulative activity involved as aircraft made their ways through the taxiway network. The average taxi times were very similar when actual schedules for the representative airport were used instead and when minor adjustments were made to model parameters that affect taxi times. They increased, however, in scenarios where traffic was intensified to a point where congestion occurred. In heavy taxi scenarios, more “taxi time” is attributable to waiting time for taxiway segments to become available.

Taxi times are also affected by judicious holding of aircraft at their departure gates by ATC when there is a backlog of aircraft ready to depart. Such “gate holds” resulted in reduced taxi

times but longer nominal delays for affected aircraft in the performance statistics. (The researchers recorded the departure time for each aircraft as the time of its “pushback” rather than the time at which the aircraft reported its status to ATC as “ready for pushback.”)



## DATA FOR MODEL CALIBRATION

The researchers use the term “turnaround” to represent the activity for an aircraft between its approach inbound from the previous airport to its departure outbound to the next airport. To calibrate the model in a specific setting, using an entire year’s data for each scheduled flight is recommended. Ideally, the dataset would include the tail number of the aircraft for each flight so that the complete turnaround of the aircraft can be modeled, rather than treating arrivals and departures independently of each other. While most aspects of airside activity can be reasonably modeled without necessarily matching the aircraft to inbound and outbound flights, better simulated performance statistics for individual carriers can be produced with the matched data.

For this research, the aircraft ID (tail number) was used by the AOC to match inbound and outbound movements for the turnarounds. Included in the data were (1) arrival date, (2) arriving flight number with airline designator and flight number, (3) arrival gate (parking stand), (4) arriving aircraft tail number, (5) aircraft type, (6) previous airport for the inbound flight, (7) originating airport for the inbound flight, (8) scheduled time of arrival, (9) time airplane touched down on arrival, (10) actual time of arrival at the gate, (11) departing flight number, (12) gate from which the aircraft departed, (13) next airport for the flight, (14) destination airport for the flight, (15) scheduled departure time, (16) pushback time, and (17) liftoff time. From the gate numbers, the researchers identified the parking sections using the mappings from Table 1.

Geographic coordinates were obtained for each of the “previous” and “next” airports by matching the three-character airport codes with those in the International Airline Transport Association (IATA) online database. By comparing the longitude and latitude of connected airports with those of the focal airport, the true bearing from the focal airport and the great-circle distance for the flight were determined. Flights with bearings between 0 and 90 degrees were designated as approaching and departing from the northeast sector, flights with bearings between 91 and 180 degrees as approaching and departing from the southeast sector, flights with bearings between 181 and 270 degrees as approaching and departing from the southwest sector, and flights with bearings between 271 and 359 degrees as approaching and departing from the northwest sector. These data were used to define flight corridors and to allow specification of maximum hourly flow controls (inbound and outbound) for each flight corridor.

## HISTORICAL ANALYSIS OF FLIGHT OPERATIONS

Key performance statistics for flights and the status of airport operations include the following:

- Number of aircraft parked at gates, taxiing both inbound and outbound
- Taxiing times inbound (minutes from time of touchdown to time parked at the gate, including times waiting on taxiways and ramps)
- Delays in arrival (difference in minutes between the actual time the aircraft arrived at the gate and the scheduled time for arrival at the gate)
- Delays with pushback (difference in minutes between the actual time that the plane was pushed back from the gate and the scheduled time of departure)
- Taxiing times outbound (minutes from pushback to the time that the aircraft lifted off for departure, including times waiting on ramps and taxiways)

These vary by time of day because schedules are concentrated in busy periods desired by passengers and airlines. As part of the calibration process, the researchers compared these statistics for simulated and actual flights by time of day. These statistics were also examined according to the combination of runway used and parking section for respective arrivals and departures. Other comparisons may be drawn according to type (class) of aircraft and carrier name.

From the historical data, the status of the airport at each moment in time was deduced. When accounting for the number of aircraft parked at gates (taxiing in and out), the statistics were reset at the beginning of each day (midnight) according to the activity that spanned (began before and ended after) midnight at the beginning of that day. Flights that touched down before midnight but were not shown to have arrived at the gate were determined to be taxiing in. Flights that had arrived at the gate but had not yet been pushed back were determined to be parked at the gate. Flights that were pushed back before midnight but were not yet lifted off were considered to be taxiing out. The tallies were reset in this fashion to avoid cumulative errors that might creep in from missed recordings of events or from incomplete data at times when new data with records of activity were appended.

From the data, a SAS dataset of historical “flight turns” was created, which was used for building statistical models that were used to represent systematic and random variation in approach times for flights in a schedule and movements of aircraft from the time they touched down on the runway to the time they lifted off for departure.

Randomness in approach times (arrival delays) was imposed externally to the simulation model and represented in an input data file that was read by the simulation model. Randomness in elemental events in the flow of aircraft through the airport environment (which contributes to departure delays) was incorporated within the simulation model. Figure 3 illustrates an excerpt of tallies that show the status of an airport at midnight on different days of a chosen week.

*Initial States for Midnight Each Day between 9/1/2015 and 8/31/2016*

Obs	Date and Time	Date	Parked	Taxiing Inbound	Taxiing Outbound	Total Planes on Field
1	01SEP15:00:00	2015-09-01	28	1	1	30
2	02SEP15:00:00	2015-09-02	39	1	1	41
3	03SEP15:00:00	2015-09-03	29	1	1	31
4	04SEP15:00:00	2015-09-04	27	2	0	29
5	05SEP15:00:00	2015-09-05	34	0	3	37
6	06SEP15:00:00	2015-09-06	32	0	0	32

**Figure 3. Excerpt from initial states**

## IMPOSING VARIATION IN ARRIVAL AND TURNAROUND TIMES

The researchers used statistical models to impose systematic and random variation in arrival and turnaround times for individual flights. The first element of variation occurred in the time at which planes approach the airport for landing. CHAID decision trees were constructed (using Statistical Package for Social Sciences [SPSS]) to search for systematic patterns in delays. Arrival delays were shown to vary by hour of day and to involve a complex interaction among individual airlines, month of the year, international versus domestic flights, ATC region of the previous airport, and inbound bearing from the previous airport. Length of departure delays varied according to the time available to turn around the airplane (differences between scheduled time of departure and actual time of arrival), month of the year, scheduled hour of departure, individual airline, outbound bearing to the next airport, international versus domestic flights, ATC region for the next airport, and whether the flight involved the use of a passenger bridge for boarding.

Logistic equations were fit using these variables to capture systematic variation in the likelihoods of delay. Regression equations were fit to represent systematic variations in the lengths of delays or turnaround times leading to delays.

The times for simulated arrivals were generated by estimating the arrival delay experienced by a flight and offsetting the time at which the aircraft entered local airspace by the average time to reach the arrival gate from the final approach fix. Examples of the equations used to accomplish this are as follows:

```
* Expected Delay (minutes) for Any Arrival ;
* model fitted 22JUN17 13:42 ;
expminarrdelay=-constant (suppressed for confidentiality) +(7.6501080072 ) *
schedarrtento4pm +(12.294610433 ) * schedarrafter4pm +(14.275627316 ) * intarriv +(0
) * nedep_sector +(-1.070436186 ) * nwarr_sector +(9.5887862738 ) * searr_sector
+(19.751689797 ) * light +(-8.954452357
) * heavy +(9.1787270506 ) * summer +(4.1082333963 ) * fall +(0 ) * winter ;

* stderr = 28.437719459 ;

avminarrdelay = 10.017973588 ;
* based on 79,283 observations;
* with alpha = .05 for stepwise addition and elimination of variables;
* where minutesarrdelay ge -30 and minutesarrdelay le 120;

delay= max(-20,int(expminarrdelay+ 28.4*normal(1111)));
schedfafminofday=max(0,schedarrminofday-&offsettofaf);
arrivfafminuteofday = int(max(0,schedfafminofday+delay));
```

The equations above created delays that followed a truncated normal distribution (with planes that arrive no more than 20 minutes early) for arrivals at the final approach fix. In the regression models for delays illustrated here, the researchers did not consider the airline that operates the flight, though the airline is a significant explanatory factor. This preserves confidentiality of the airline data and makes it easy to generate random arrivals for intensified schedules without having to designate what airline was operating the new flights. (Delay statistics for an individual airline can change dramatically if the airlines alter the cushions they provide in their schedules or change the way that flights at that airport are integrated into their schedule with possible changes in crew assignments.)

Systematic variation in turnaround times was imposed differently for flights requiring immediate turnarounds versus nonimmediate turnarounds. The former, which involved flights with less than 31 minutes between the scheduled departure time and the time at which the aircraft arrives at the gate, was imposed by using a regression model for the expected turnaround time. The latter, which involved flights with more than 30 minutes between the actual arrival time and scheduled departure time, were imposed by a logistic model for the likelihood of delay and a regression model for length of delay. Examples equations are as follows:

```
* Expected Turnaround Minutes for Immediate Turnarounds (30 minutes or less to turn
plane) ;
* model fitted 22JUN17 13:42 ;
expturntimeimmturn=constant (suppressed for confidentiality) +(-0.030469194 ) *
availturnmin +(23.515765477 ) * scheddephour7 +(6.9381070985 ) * scheddephour8
+(13.936018881 ) * scheddephour9 +(6.7255801778 ) * scheddephour10
+(6.3232851553 ) * scheddephour11 +(10.084182037 ) *
scheddephour12 +(12.569193078 ) * scheddephour13 +(8.6761652097 ) *
scheddephour14 +(6.8775280931 ) * scheddephour15 +(8.6935581212 ) *
scheddephour16 +(6.2769836326 ) * scheddephour17 +(8.4241928731 ) *
scheddephour18 +(7.6855683636 ) * scheddephour19 +(
10.765986752 ) * scheddephour20 +(11.209316465 ) * scheddephour21 +(6.7656282308
) * scheddephour22 +(0 ) * scheddephour23 +(1.7781188678 ) * intarriv +(12.077074937
) * intdep +(-2.334416934 ) * nedep_sector +(-3.096617541 ) * nwdep_sector +(0 ) *
sedep_sector +(-5.467365513 ) * passbridge +(0 ) * light +(-15.6351387 ) * medium +(0
) * heavy +(9.692480402 ) * summer +(-2.019672676 ) * fall +(0 ) * winter ;

* stderr = 18.372657291 ;

avturntimeimmturn = 50.754045707 ;
* based on 16,190 observations;
* with alpha = .05 for stepwise addition and elimination of variables;
* where immediatelyturnaround eq 1 and turntime ge 15 and turntime le 120; ;
```

A corresponding equation that gives the length of departure delay for an immediate turnaround is as follows:

\* Expected Delay (minutes) for Immediate Turnarounds (30 minutes or less to turn plane)  
 ;  
 \* model fitted 22JUN17 13:42 ;  
 expmindepdelayimturn= constant (suppressed for confidentiality) +(-1.754602246 ) \*  
 availturnmin +(0 ) \* scheddephour7 +(0 ) \* scheddephour8 +(0 ) \* scheddephour9 +(0 ) \*  
 scheddephour10 +(0 ) \* scheddephour11 +(0 ) \* scheddephour12 +(5.7284621183 ) \*  
 scheddephour13 +(1.6379652426 ) \* scheddephour14 +(0 ) \* scheddephour15  
 +(2.1211747209 ) \* scheddephour16 +(0 ) \* scheddephour17 +(0 ) \* scheddephour18 +(0  
 ) \* scheddephour19 +(3.6195489029 ) \* scheddephour20 +(5.0319282425 ) \*  
 scheddephour21 +(2.7005853306 ) \* scheddephour22  
 +(-4.287267703 ) \* scheddephour23 +(0 ) \* intarriv +(11.834570359 ) \* intdep +(-  
 1.98812569 ) \* nedep\_sector +(-2.952211442 ) \* nwdep\_sector +(0 ) \* sedep\_sector +(-  
 4.037184453 ) \* passbridge +(0 ) \* light +(0 ) \* medium +(17.704084291 ) \* heavy  
 +(9.4297509673 ) \* summer +(-2.692440724 ) \* fall +(0 ) \* winter ;  
  
 \* stderr = 22.42696136 ;  
  
 avmindepdelayimturn = constant (suppressed for confidentiality) ;  
 \* based on 13,481 observations;  
 \* with alpha = .05 for stepwise addition and elimination of variables;  
 \* where immediatelyturnaround eq 1 and minutesdepdelay ge -5 and minutesdepdelay le  
 120;

Note how delays tend to be longer as the day progresses, a general phenomenon that occurs widely as flight delays propagate through the day. Note also how the expected delay is less if there is more time to turn the airplane around. Expected delays are longer in the summer (with a greater prevalence of thunderstorms) and generally higher traffic levels, and, in this instance, delays are more likely for international arrivals and less likely if passenger bridges are available for boarding. The average minutes delay may seem large, but remember that this equation applies only to flights requiring an immediate turnaround (usually because of a late arrival).

For nonimmediate turnarounds, the likelihood of delay was estimated with a logistic equation like the following:

Equation for nonimmediate turnarounds (avail turn time gt 30) ;  
 \* model fitted 23JUN17:14:59:16 ;  
 probdepdelay = 1/(1+exp(  
 - Constant (suppressed for confidentiality)  
 + ( 0.0042448858 ) \* availturnmin  
 + ( -0.120793886 ) \* scheddephour7  
 + ( 0.316813925 ) \* scheddephour8  
 + ( 0 ) \* scheddephour9  
 + ( 0.6513289704 ) \* scheddephour10  
 + ( 0.3649295479 ) \* scheddephour11  
 + ( -0.112981277 ) \* scheddephour12  
 + ( -0.374566297 ) \* scheddephour13

+ ( 0.0813064495 ) \* scheddephour14  
 + ( -0.283280659 ) \* scheddephour15  
 + ( -0.117581442 ) \* scheddephour16  
 + ( 0 ) \* scheddephour17  
 + ( 0 ) \* scheddephour18  
 + ( 0 ) \* scheddephour19  
 + ( 0 ) \* scheddephour20  
 + ( 0 ) \* scheddephour21  
 + ( -0.35178963 ) \* scheddephour22  
 + ( 0.3787827019 ) \* scheddephour23  
 + ( -0.469927466 ) \* intarriv  
 + ( -0.694063504 ) \* intdep  
 + ( -0.099432278 ) \* nedep\_sector  
 + ( 0.608458539 ) \* nwdep\_sector  
 + ( -0.182221669 ) \* sedep\_sector  
 + ( 0.5004434266 ) \* passbridge  
 + ( 0 ) \* light  
 + ( 0.5782542207 ) \* medium  
 + ( 0 ) \* heavy  
 + ( -0.794558341 ) \* summer  
 + ( 0 ) \* fall  
 + ( 0 ) \* winter  
 ));  
 \* with alpha = .05 for stepwise addition and elimination of variables;

avprobdpdelay = constant (suppressed for confidentiality) ;  
 \* based on all 66,157 observations;  
 \* where immediatelyturnaround eq 0; ;

This equation is a logistic expression normed on “no delay,” so the directional effects are opposite of the signs of the logistic coefficients, which appear only in the denominator of the logistic expression. Other things considered, departure delays are more likely in the summer months and for international departures, generally more likely in the afternoon than in the morning, and less likely if a passenger bridge is employed.

Considering systematic variation in the length of delays when delays do occur, the regression equation is as follows:

\* Expected Delay (minutes) for Nonimmediate Departures ;  
 \* model fitted 22JUN17 13:42 ;  
 expmindepdelay=constant (suppressed for confidentiality)  
 +(0.0199422663 ) \* availturnmin +(-1.892163481 ) \* scheddephour7 +(-8.970085861 )  
 \* scheddephour8 +(-4.99107496 ) \* scheddephour9 +(-5.153172508 ) \* scheddephour10  
 +(-4.286860189 ) \* scheddephour11 +(-2.070431426 ) \*  
 scheddephour12 +(1.7646256981 ) \* scheddephour13 +(0 ) \* scheddephour14  
 +(4.4077374747 ) \* scheddephour15 +(0 ) \* scheddephour16 +(0 ) \* scheddephour17 +(0

```

) * scheddephour18 +(1.2645898921 ) * scheddephour19 +(0 ) * scheddephour20
+(2.803190787 ) *
scheddephour21 +(4.3249481428 ) * scheddephour22 +(-2.168050932 ) *
scheddephour23 +(4.6682275399 ) * intarriv +(5.7467082844 ) * intdep +(-2.034770366
) * nedep_sector +(-5.960525808 ) * nwdep_sector +(5.6878057037 ) * sedep_sector +(-
3.22911969 ) *
passbridge +(0 ) * light +(-5.114089596 ) * medium +(0 ) * heavy +(10.084123281 ) *
summer +(-0.93516492 ) * fall +(0 ) * winter ;

* stderr = 22.051735183 ;

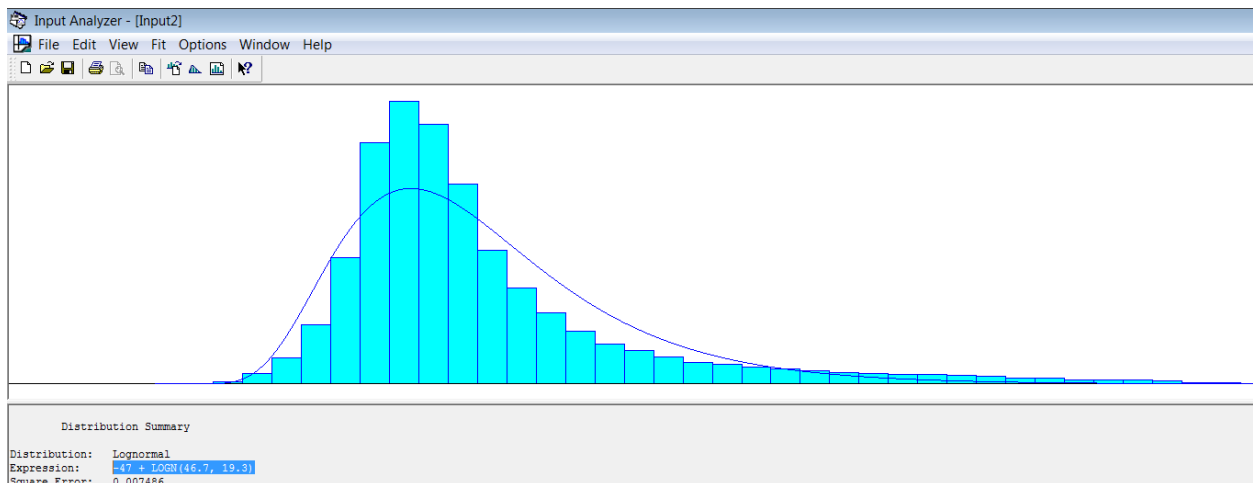
avmindepdelay = constant (suppressed for confidentiality) ;
* based on 48,545 observations;
* with alpha = .05 for stepwise addition and elimination of variables;
* where immediateturnaround eq 0 and minutesdepdelay ge -5 and minutesdepdelay le
120; ;

```

For nonimmediate departures, the average delay is much lower but the effects of the other variables are similar.

Finally, residual (unsystematic) variation was imposed on the time at which the plane reported to ATC that it was ready for pushback. For the residual variation of nonimmediate turnarounds, residuals were fit from the statistical models for delays. For residual variation of immediate turnarounds, the residual deviations of statistical models for turnaround time were fit. And to fit the residual distributions, an Arena input analyzer was used.

The best fit for nonimmediate delay residuals turned out to be an offset lognormal distribution with expression  $\text{residualdelaynonimm} = -47 + \text{LOGN}(46.7, 19.3)$ , obtained as illustrated in Figure 4.



**Figure 4. Residual variation in pushback delays relative to scheduled departure time**



For immediate turnarounds, the corresponding expression for residual variation in turn times, based on 16,190 departures, was similarly  $\text{residualimmturn} = -\text{constant}$  (suppressed for confidentiality) +  $\text{LOGN}(\text{constant}, 18)$ .

Because the researchers only had tail numbers in this experimental environment (for all arrivals and departures), only aircraft parked on the field at midnight were considered to be “originating” flights, and their effect on delay statistics was minor. The same random distribution was therefore used to determine departure delays for originating flights.

The resulting turn time is the sum of the expected turn time plus residual deviation, computed as follows:

$$\begin{aligned} \text{Turntime} = & (\text{availturnmin} \leq 30) * (\text{turtimeimmturn} + \text{residualimmturn}) \\ & + (\text{availturnmin} > 30) * (\text{availturnmin} + (\text{expdepdelaynonimm} + \text{residualdelaynonimm}) \\ & * \text{probdepdelaynonimmturn}). \end{aligned}$$

When an aircraft was “ready for pushback,” a tractor was engaged to push back the aircraft (if necessary for the particular gate). It was assumed that no connecting time was required unless all tractors that served the gate were engaged with other aircraft. In such instances, a triangular distribution was used for time to engage the tractor. Pushback times (from the start of pushback to release of the tractor) were generated according to the following expression:

$$\begin{aligned} & \text{bridge} * \text{logn}(\text{avpptime}, \text{avpptime} * \text{cvpptime}) \\ & + .9 * (1 - \text{bridge}) * \text{logn}(\text{avpptime}, \text{avpptime} * \text{cvpptime}) \end{aligned}$$

If no parking bridge was used, pushback times were reduced by 10%.

## USE OF THE SIMULATION MODEL FOR STRATEGIC ANALYSIS

Examples of strategic questions that may be addressed with help from the simulation model include the following:

- What are the key constraints in accommodating future growth in traffic?
- What are the consequences of changing how runways are used for arrivals and departures?
- How does performance depend on the positioning and range of activity of tractors used to push back aircraft that are parked at gates or parking stands that require such service?
- How does performance depend on the assignment of preferred parking sections to individual flights and on rules for selecting alternative parking sections if no spots are available in the preferred parking section when an aircraft arrives?
- What are the consequences of changing scheduled arrivals and departures (shifting scheduled arrival and departure times for existing flights or adding new flights)?

Table 6 lists the primary experimental factors that may be addressed with help from the model and how they are incorporated.

**Table 6. Primary experimental factors**

<b>Experimental Factor</b>	<b>How Incorporated in the Simulation Model</b>
Flight turns (schedules) to be simulated with schedule information (previous airport, next airport, aircraft ID, flight numbers, aircraft type, whether international, airspace sector for arrival and departure, preferred gate or parking section, scheduled arrival and departure times)	Provided by airport planning department or derived from historical flights and read by the simulation model from an external file sorted by simulated arrival time and subsequent schedule for the departing flight of the aircraft
Future flight turns (intensified schedules with traffic growth)	Generated with consideration of desired percentage increase in flights, hour-of-day patterns for existing and new flights, and proportion of new flights of different types (e.g., international flight or heavy aircraft) to be assigned to each “preferred” parking section
Initial status (planes at gate at midnight)	Read from a file of “originating” flights with gate assignment and scheduled “flight turn” data
Runway usage (which RWY to use for each arrival and departure and may depend on parking section)	By assigning a runway index for each arrival or departure using a mathematical “expression” in the simulation model
Gates in use and gate capacity (number of aircraft that the gate can handle—usually one)	By adjusting gate capacity for defined gates (gate resources) in the model
Passenger bridge or parking stand indicator for each gate	Stipulated in a file with section and gate indices as input data for the simulation model (specified in SAS format statements in the SAS programs for reporting and analysis)

Experimental Factor	How Incorporated in the Simulation Model
Tractors for pushbacks (pushback service is provided to flights from gates or parking stands that physically require pushbacks); Some airlines may be assumed to have tractors of their own available when needed except for a designated percentage of flights that will use tractors provided by the airport	Sets of tractor resources are assigned to designated gate groups that determine their range of activity and may include parts of different parking sections; Tractors are selected for pushbacks from defined (and overlapping) resource sets (these may be altered by changing the definition of resource sets in the simulation model)
Process times (taxi speeds, approach speeds, crossing-intersection times, crossing-ramp times, pushback times when ready and attached to tractor, repositioning times for tractors)	Embedded in the model as expressions or global variables
Arrival delays	Imposed randomly and externally based on statistical models and reflected in the approach times for flight turns.

Setup of the model for chosen scenarios and growth in traffic includes the following:

- Designation of files with input data. Input files were created for the base schedule (August 2016) and for increases in traffic of 20, 40, 60 and 80%, assuming roughly the same pattern of traffic intensity at different times of the day.
- Designation of output files for the simulation event log and tractor usage. These were used externally for generating comprehensive reports of airside performance under the chosen scenario and operating rules. With proper naming conventions, reports can be saved for the different scenarios, which provide audit trails for statistical results.
- Resetting initial values of user-defined global variables (that the user may wish to change) is described in Appendix A (e.g., *Winddir* for wind direction, which determines runway use).
- Resetting user-defined expressions is also described in Appendix A (e.g., *arrivrwyindicator*, which determines the runway to be used by an arriving aircraft and *deptrwyindicator*, which determines the runway to be used for a departing aircraft).
- Resetting Arena-defined global variables such as resource capacities (e.g., implicitly changing MR(tractor1) when stipulating the resource capacity for tractor1). Major infrastructure parameters include the gates available in each parking section and capacities for staging points on the airport surface to accommodate inbound and outbound aircraft.
- Possibly changing expressions that control the movement of aircraft through the system. Air traffic controllers, for example, hold planes at gates if more outbound flights are ready to leave than can be accommodated in the departing airspace sector considering weather, other traffic in the local airspace, conditions at destination airports, and separation standards for wake turbulence and general safety.

For the base case in the simulation experiments, the researchers choose a daily schedule where no major disruptions occurred at a busy time of the year.

## MODEL CALIBRATION AND VALIDATION

Hundreds of statistics were generated and reported with details about system performance. Detailed event logs allow the user to examine the sequence of key events for each flight according to time of day and individual aircraft. Model validation included the following:

- Examining detailed event logs of simulated activity to see if the sequence of events is consistent with actual airport operations
- Examining summary statistics of activities at each hour of the day to ensure that the intensity varies consistently with daily patterns
- Examining statistics for inbound and outbound taxi times for each parking section to ensure that they reflect the taxi distances involved as different runways are used for arrivals and departures
- Examining delay statistics to see if they are consistent with historical data under prevailing weather conditions and operating constraints
- Testing “disruptive” scenarios to see if the results are logically consistent, and, to the extent that data are available, with actual performance under similar disruptions

The purpose of the simulation model was to accommodate deviations that naturally occur in actual operations while allowing the creation of scenarios for major disruptions. Equations for imposing systematic changes in performance were constructed with the screening of “outliers.” The more observations that were removed as unusual, the lower the variability in simulated activity from one simulated day to the next. With less variability, there tended to be a reduction in delays. One can refit the component statistical models with different levels of screening or reduce the level of random variation in the model to test whether inferences about performance under different operating assumptions are robust. Indeed, periodic updates are recommended using a full year of data because the operating environment can change as managers continuously try to improve operations and as airlines adjust their schedules and ground support to optimize performance within their networks.

To give a sense of the extent to which the model reasonably depicted true operations versus an operational ideal, the following summaries of hourly activities for a particular day’s schedule are provided:

- If everything were to happen exactly according to schedule (i.e., with every arrival and departure occurring exactly on time)
- As it actually did occur on that day
- As represented in a single day of simulated activity
- As represented in 100 days of simulated activity.

This comparison was based on simulations of landings on RWY 07 and takeoffs on RWY 06, under a summer scenario where delays are more likely than in the fall and winter. Remember that the model imposes variation that will occur for each flight under a variety of conditions, but

without major disruptions of the type that occur in extreme instances, which were removed when the researchers constructed the statistical models for arrival delays and turnaround times. The simulated performance reported in Figures 5 to 13 is based on a calibration where delays over 120 minutes were screened out.

Experiments were conducted in which the researchers reconstructed the statistical models for arrival delays and turnaround times after changing the screening criterion for outliers. A tighter screening criterion (i.e., screening out a higher percentage of data points) tended to reduce random variation in simulated performance and make it easier to detect small differences in performance among scenarios, but it also tended to reduce the number of larger disruptions that occasionally occurred. Strategic inferences from application of the model seemed to be quite robust under different screening criteria. Resulting delays for simulated flights increased, as expected, when a wider screen was used to calibrate the delay equations, but the inferred impacts of strategic changes in infrastructure and operations were quite similar.

Figures 5 to 13 demonstrate how the model captures the effects of randomness in arrival times, ground movements, turn time for ground services, and tractor engagements. Figure 5 shows the hourly activity that would take place on the airfield if every flight were to operate exactly according to schedule, assuming average times overall for taxiing into gates after landing and taxiing outbound for takeoff. There would be a maximum of four aircraft taxiing inbound and outbound at different times of the day.

hour	Av. Num. Planes Taxiing In	Av. Num. Planes Parked	Av. Nnum. Planes Taxiing Out	Max Num. Planes Taxiing In	Max Num. Planes Taxiing Out	Max Num. Planes Parked
0	0.0	13.3	0.0	1	1	33
1	0.6	37.9	0.0	2	0	42
2	0.7	45.3	0.0	3	0	50
3	0.0	51.1	0.0	1	1	52
4	0.0	51.1	0.0	1	1	52
5	0.0	51.1	0.0	1	1	52
6	0.0	44.9	0.7	0	2	50
7	0.0	32.7	1.0	1	3	40
8	0.1	14.0	0.7	2	3	22
9	0.4	17.8	0.3	4	3	23
10	0.1	21.5	0.5	4	2	24
11	0.3	19.9	0.6	4	4	26
12	0.2	23.7	0.6	3	4	25
13	0.3	25.0	0.5	3	3	28
14	0.1	23.2	0.8	3	4	27
15	0.3	24.9	0.6	3	3	26
16	0.3	23.7	0.7	3	4	26
17	0.2	22.0	0.6	2	3	24
18	0.2	20.7	0.6	2	3	22
19	0.3	24.4	0.4	4	2	28
20	0.1	21.9	0.9	3	3	27
21	0.2	20.7	0.6	3	4	23
22	0.1	20.1	0.4	3	2	23
23	0.4	25.8	0.0	3	1	31

**Figure 5. Hourly activities if all operations occur exactly according to the day’s schedule**

Using actual statistics for the same day, Figure 6 shows that bunching of activity occurs even on days without major weather disruptions.

Hour of Day	Av. Num Planes Parked	Max Num Planes Parked	Av. Num Planes Taxiing	Max Num Planes Taxiing	AV. Num Taxiing Inbound	Max Num Taxiing Inbound	Av. Num Taxiing Outbound	Max Num Taxiing Outbound
0	32.8	35	0.9	6	0.6	3	0.4	3
1	38.7	42	1.1	6	0.9	3	0.2	3
2	44.8	47	0.6	6	0.5	3	0.1	3
3	35.4	46	3.2	6	1.5	3	1.8	3
4	24.0	24	6.0	6	3.0	3	3.0	3
5	24.0	24	6.0	6	3.0	3	3.0	3
6	39.4	45	2.4	6	0.6	3	1.8	3
7	31.8	42	5.9	12	0.4	3	5.5	9
8	20.0	25	5.8	10	1.1	3	4.8	7
9	21.8	28	5.0	9	2.4	5	2.6	4
10	27.5	32	6.6	12	2.0	4	4.6	8
11	25.1	28	6.8	11	2.0	4	4.8	7
12	29.3	32	6.8	12	2.2	4	4.6	8
13	25.0	29	8.4	14	1.4	3	6.9	11
14	24.8	28	7.0	11	2.4	4	4.7	7
15	28.7	33	7.2	13	2.2	4	5.1	9
16	26.8	29	7.4	14	2.0	4	5.5	10
17	24.9	27	9.2	13	2.8	4	6.4	9
18	23.4	28	7.5	13	1.5	4	6.0	9
19	26.6	33	4.5	8	2.1	4	2.4	4
20	32.4	34	5.5	12	1.3	3	4.3	9
21	26.8	31	6.8	12	2.2	4	4.6	8
22	26.1	31	6.6	12	1.0	4	5.5	8
23	25.1	27	3.0	7	1.0	3	2.0	4
24	.	24	.	6	.	3	.	3

**Figure 6. Actual hourly activities**

Bunching is greater for departing aircraft than arriving aircraft. Up to 11 planes were taxiing outbound at times of peak activity while a maximum of 5 planes were taxiing inbound. Remember that planes taxiing inbound or outbound included those on ramps, staging points, and taxiways. Arriving planes can be held up waiting for an available gate and departing planes as pilots complete cockpit checks and await ATC clearances for taxiing and takeoff.

Simulated patterns of a single day's daily activity, as presented in Figure 7, display this same behavior.

Hour of Day	Av. Num Planes Parked	Max Num Planes Parked	Av. Num Planes Taxiing	Max Num Planes Taxiing	AV. Num Taxiing Inbound	Max Num Taxiing Inbound	Av. Num Taxiing Outbound	Max Num Taxiing Outbound
0	30.6	33	0.4	3	0.4	2	0.0	1
1	38.0	42	0.8	3	0.8	2	0.0	1
2	42.7	43	0.1	3	0.0	2	0.0	1
3	27.0	27	3.0	3	2.0	2	1.0	1
4	27.0	27	3.0	3	2.0	2	1.0	1
5	27.0	27	3.0	3	2.0	2	1.0	1
6	27.0	27	3.0	3	2.0	2	1.0	1
7	39.4	44	2.0	9	0.2	2	1.8	7
8	35.3	40	2.1	6	1.0	3	1.1	3
9	39.8	43	6.0	15	2.2	5	3.8	10
10	37.6	41	6.8	12	1.7	4	5.1	8
11	36.8	41	5.6	12	1.7	5	4.0	7
12	40.7	44	5.3	14	1.9	6	3.3	8
13	43.0	46	7.8	15	2.8	5	5.0	10
14	34.9	42	8.5	14	1.2	4	7.4	10
15	25.3	29	7.6	14	1.5	4	6.1	10
16	25.4	29	5.4	12	1.0	3	4.4	9
17	26.1	29	5.6	11	1.8	5	3.8	6
18	26.8	29	6.8	12	1.5	4	5.3	8
19	25.4	28	4.6	8	1.2	3	3.4	5
20	26.9	28	5.2	11	1.4	5	3.9	6
21	26.6	30	6.6	13	1.5	4	5.1	9
22	23.1	28	5.4	9	0.8	2	4.5	7
23	23.7	28	2.5	8	0.9	4	1.6	4
24	.	27	.	3	.	2	.	1

**Figure 7. Simulated hourly activities in one replication**

So also does simulated activity for 100 days, as seen in Figure 8. Over 100 days, of course, it is more likely to have instances of the number of aircraft taxiing outbound being equal to the maximum number allowed by ATC.



Hour of Day	Av. Num Planes Parked	Max Num Planes Parked	Av. Num Planes Taxiing	Max Num Planes Taxiing	AV. Num Taxiing Inbound	Max Num Taxiing Inbound	Av. Num Taxiing Outbound	Max Num Taxiing Outbound
0	26.4	37	0.4	5	0.4	4	0.0	1
1	40.4	43	0.3	6	0.3	5	0.0	1
2	42.9	43	0.0	4	0.0	3	0.0	1
3	28.0	28	3.0	3	2.0	2	1.0	1
4	28.0	28	3.0	3	2.0	2	1.0	1
5	28.0	28	3.0	3	2.0	2	1.0	1
6	40.3	44	0.8	3	0.6	2	0.2	1
7	38.7	45	2.4	10	0.2	3	2.2	7
8	34.7	41	1.7	9	0.6	5	1.1	4
9	37.5	47	5.9	18	2.0	8	4.0	10
10	38.5	46	6.1	18	2.0	8	4.1	10
11	37.4	46	6.0	18	1.9	8	4.1	10
12	41.1	50	5.8	18	2.0	8	3.7	10
13	41.9	52	7.3	19	2.5	8	4.8	11
14	34.6	45	9.4	18	1.6	8	7.8	10
15	27.7	37	7.5	16	1.5	6	5.9	10
16	27.9	37	6.1	16	1.4	6	4.7	10
17	26.7	35	6.0	16	1.4	6	4.6	10
18	24.6	34	6.2	16	1.3	6	4.9	10
19	25.5	37	5.2	17	1.5	7	3.7	10
20	27.1	35	6.2	16	1.3	6	4.9	10
21	24.4	31	5.4	15	1.2	5	4.2	10
22	23.4	31	4.9	16	1.0	6	4.0	10
23	25.0	35	2.8	14	1.0	6	1.8	8
24	.	31	.	5	.	3	.	2

**Figure 8. Hourly activity in 100 replications of the daily schedule**

Figures 9 to 11 show corresponding statistics for delays and taxi times both inbound and outbound.

		Delays (av. min. delay)		Flights with Delay > 15 min.		Ramp and Taxi time
		Flights	Av. Delay	Number over 15 min.	P(>15 min.)	Av. Minutes
section	event					
98	4: Departure	1	77.0	1	1.000	18.0
Sect 1	2: Arrival	9	8.3	2	0.222	6.4
	4: Departure	8	10.4	1	0.125	16.4
Sect 2	2: Arrival	8	11.4	2	0.250	5.9
	4: Departure	8	26.8	5	0.625	13.6
Sect 3	2: Arrival	5	72.0	4	0.800	8.2
	4: Departure	7	43.4	3	0.429	14.4
Sect 4	2: Arrival	2	9.0	0	0.000	9.0
	4: Departure	1	19.0	1	1.000	18.0
Sect 5	2: Arrival	44	16.9	15	0.341	5.1
	4: Departure	46	24.4	20	0.435	18.1
Sect 6	2: Arrival	153	13.5	39	0.255	6.5
	4: Departure	152	21.9	58	0.382	17.9
Sect 7	2: Arrival	43	16.0	14	0.326	7.8
	4: Departure	45	26.9	26	0.578	18.7
UNK	2: Arrival	10	1.1	0	0.000	8.0
	4: Departure	10	10.3	1	0.100	18.0
Overall		552	19.1	192	0.348	12.2

**Figure 9. Actual delay and taxi times for chosen day**

		Delays (av. min. delay)		Flights with Delay > 15 min.		Ramp and Taxi time
		Flights	Av. Delay	Number over 15 min.	P(>15 min.)	Av. Minutes
section	event					
Sect 1	2: Arrival	10	16.0	5	0.500	4.1
	4: Departure	8	29.0	7	0.875	10.9
Sect 2	2: Arrival	8	19.0	5	0.625	5.7
	4: Departure	7	27.3	5	0.714	8.5
Sect 3	2: Arrival	4	43.1	2	0.500	7.6
	4: Departure	4	4.9	0	0.000	8.5
Sect 4	2: Arrival	2	32.9	2	1.000	8.8
	4: Departure	2	7.1	0	0.000	10.1
Sect 5	2: Arrival	56	19.6	31	0.554	5.4
	4: Departure	57	30.0	33	0.579	15.7
Sect 6	2: Arrival	146	17.0	64	0.438	5.2
	4: Departure	147	26.5	72	0.490	15.4
Sect 7	2: Arrival	39	17.1	16	0.410	7.8
	4: Departure	42	38.7	26	0.619	20.2
China P	2: Arrival	10	10.1	4	0.400	7.9
	4: Departure	10	4.1	1	0.100	2.9
Overall		552	22.9	273	0.495	10.5

Figure 10. Simulated activity for one day with AOC-assigned gates used to indicate preferred parking sections

		Delays (av. min. delay)		Flights with Delay > 15 min.		Ramp and Taxi time
		Flights	Av. Delay	Number over 15 min.	P(>15 min.)	Av. Minutes
section	event					
Sect 1	2: Arrival	998	17.7	443	0.444	4.1
	4: Departure	800	28.5	427	0.534	11.3
Sect 2	2: Arrival	800	19.0	370	0.463	5.8
	4: Departure	700	20.9	326	0.466	9.2
Sect 3	2: Arrival	485	39.1	280	0.577	7.6
	4: Departure	400	21.8	211	0.528	8.4
Sect 4	2: Arrival	200	22.1	106	0.530	8.8
	4: Departure	197	12.2	76	0.386	9.9
Sect 5	2: Arrival	5,604	22.2	3,024	0.540	5.5
	4: Departure	5,712	34.0	3,827	0.670	16.0
Sect 6	2: Arrival	14,682	18.5	6,736	0.459	5.1
	4: Departure	14,641	27.7	7,583	0.518	15.6
Sect 7	2: Arrival	3,892	22.2	2,051	0.527	8.6
	4: Departure	4,192	41.7	2,886	0.688	19.1
China P	2: Arrival	1,000	14.0	363	0.363	8.0
	4: Departure	1,000	5.5	97	0.097	3.0
Overall		55,303	25.0	28806	0.521	10.6

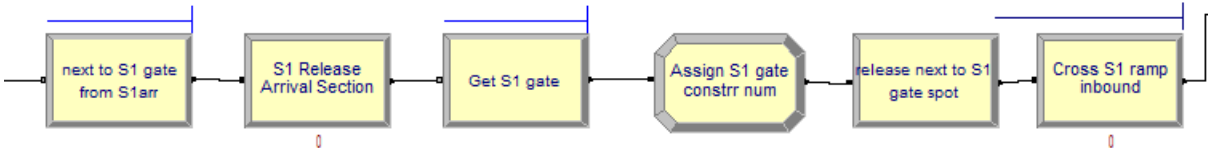
**Figure 11. Simulated activity for 100 days with AOC-assigned gates used to indicate preferred parking sections**

The simulated performance statistics depend on probability distributions for elemental activities, which can vary for different parking sections. Fine-tuning of the model may include adjustments to probability distributions for the following:

- Average taxi speeds
- Times to cross intersections
- Tractor pushback times after a plane signals its readiness for departure (average was set at 5 minutes based on AOC and maintenance department advice)
- Times to cross ramps from the arrival staging points for parking sections and reach the assigned gate (perking position)
- Residual delays after pushback for pilot checklists and clearance to taxi
- Times to cross ramps from assigned gates to departure staging points for parking sections.

Calibration of the model did not include time studies for these parameters in individual parking sections or for individual airlines. Such refinement would be needed only in sections of the

airport where special studies of congestion are required. Figure 12 illustrates elemental process blocks in the Arena model where an adjustment to ramp crossing times in Parking Section 1 could be made.



**Figure 12. Process blocks for crossing ramp in Parking Section 1**

## DEFINING SCENARIOS IN THE ARENA MODEL FOR STRATEGIC ANALYSIS

In this section, the researchers illustrate how changes were imposed for strategic analysis of groundside operations. Some involved changing input data. Others involved changing values of variables and expressions in the model itself. Appendix A contains a list of user-defined variables and expressions for this purpose.

### Altering Flight Schedules (Especially to Increase Traffic Levels)

Increasing traffic was accomplished by providing new input files with the desired number of additional flights. They were given suffixes like i20pct, etc. Users should be aware that performance statistics from the simulation model (and in practice) will be affected by a mix of new flights in the schedule (airlines involved, size of aircraft, whether the inbound and outbound flights are international), preferred parking sections assigned to each flight, rules for parking section reassignments, and the times at which arrivals and departures are scheduled to occur.

Using the files provided, set the traffic scenario in the Arena program by changing i00pct in the file name suffixes for the desired scenario (e.g., i40pct), including the files for the event log and tractor usage log.

Clicking in the Arena model window and performing a global change using *Edit > replace all* should produce four new file names.

- Run the Arena model with animation for one replication and then observe dashboards (illustrated in Figures 13 and 14) to check for bottlenecks.
  - Tractor usage
  - Planes parked and taxiing for each parking section
  - Arrivals and departures, runway usage, planes held for departure
  - Planes held up in queues (shown in the logical sections in Figure 15)

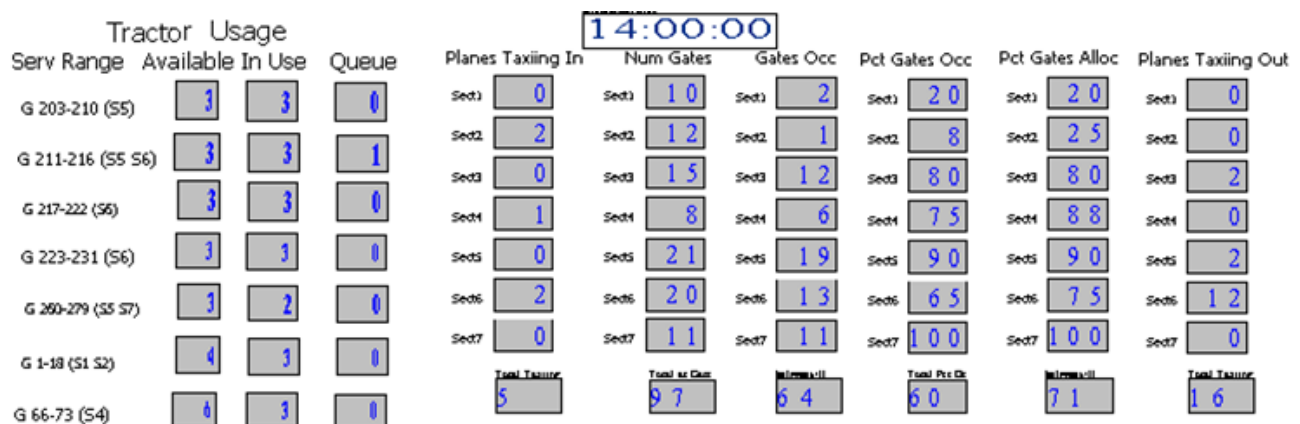


Figure 13. Animated performance dashboards for tractor usage and gate activity

## Runway Usage by ATC

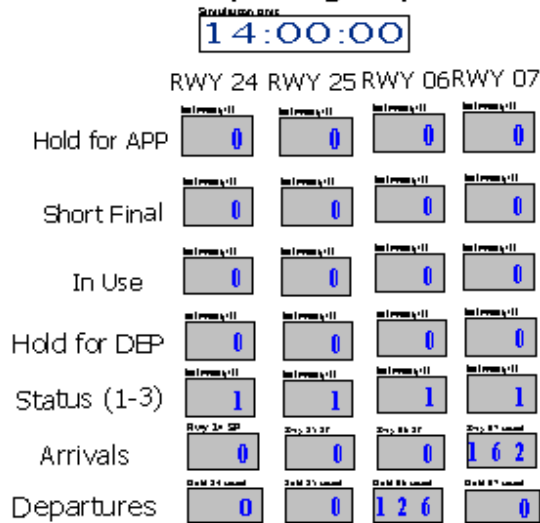


Figure 14. Dashboard for ATC runway usage

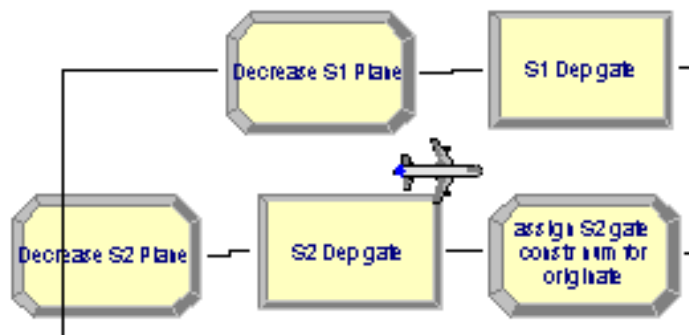


Figure 15. Queue animated in-process flow

- Run the SAS program to generate three sets of reports for the traffic and operating scenario.
- Compare performance reports with those of the base case (i00pct) to see the impact of higher traffic levels on delays, taxi times, tractor usage, wait times, etc.
- If stable performance is evident, suppress animation and run multiple replications for statistical analysis.

### Changing Runway Usage

Set the variable *winddir* to “NE” (to use RWY 07 and RWY 06) or “SW” (to use RWY 25 and RWY 24). Then set expressions for fixed or mixed use accordingly.

#### Fixed Use

Change expressions for *arrivrwyindicator* and *deptrwyindicator* to appropriate index (1 = RWY 24, 2 = RWY 25, 3 = RWY 06, 4 = RWY 27).

### Mixed Use

Change expressions for *arrivrwyindicator* and *deptrwyindicator* to refer to expressions for desired mixed use.

Examples:

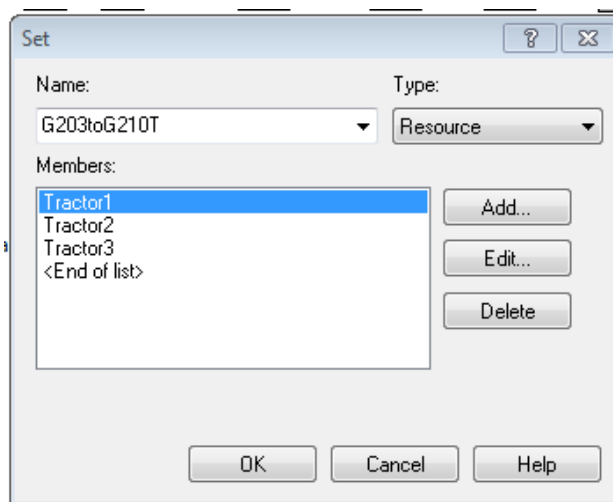
```
Mixedarrsw= 1*(section==1)+1*(section==2)+1*(section==3)
+1*(section==8)+1*(section==9) +2*(section==5) +1*(section==6)+2*(section==7)
+1*(section==4)
Mixeddepsw= 1*(section==1)+1*(section==2)+1*(section==3)+1*(section==4)
+1*(section==8)+1*(section==9) +2*(section==5)+1*(section==6)+2*(section==7)
```

*Arrivrwyindicator* = 2 and *deptrwyindicator* = *Mixeddepsw* would then cause all arrivals to use RWY 25, departures for Sections 5 and 7 to use RWY 25, and departures from other sections to use RWY 24.

### Changing Tractor Availability, Preferences, and Range of Activity

Resources for tractors are defined as tractor1 through tractor7 (see Figure 16). Capacities for each of these may be set to 0, 1, or more.

- Tractor resource sets are defined for groups of gates to determine which tractors can serve gates in the group and the order in which tractors are selected when available. They can be modified by *basic process > set >*.
- Gates 203 through 210, in this setup, would be served by tractor1, tractor2, and tractor3, in that order.



**Figure 16. Changing tractor availability, preferences, and range of activity**



## Changing Capacities in Airport Infrastructure

To alter the number of usable gates in each parking section, use *process > resource > resource name* and click on the relevant resource to change its capacity.

The capacity of a gate (number of airplanes that may be accommodated) is usually 1. The number of usable gates in a parking section may, however, be increased just by changing the capacity of one or more of the named gates in that parking section. Gates may be removed from service by setting their capacities to 0.

If animation to a newly added gate is desired (though not likely needed), it would be necessary to add corresponding stations and route blocks between the new stations and existing stations.

To alter the number of planes allowed to simultaneously occupy individual taxiway segments and staging points for arrivals and departures, use *basic process > resource > view > splitscreen* to conveniently alter capacities of resources such as the following:

- Aeast (taxiway segment that is part of Hotspot 3)
- “S1S6 ramp” (staging area on Apron 3 for activity at relevant Section 1 and Section 6 gates)
- Rsect5dept (staging point for departures from Section 5).

## Limiting Traffic in Hotspots

The numbers of planes allowed to occupy hotspots on the airport surface is determined by altering the capacities of the component resources for the respective hotspots. The total capacities of taxiway segments Deast, Aeast, C13, and C14, for example, represent the number of planes allowed to occupy Hotspot 3 near the east end of RWY 25.

The researchers did not model detailed traffic movements (e.g., to re-sequence flight movements) within hotspots or along taxiways. Instead, the number of active planes in them were limited to a number that would leave ATC ground control flexibility to use their judgment and exercise normal control of such ground maneuvers. The current number of planes occupying Hotspot 3 (and the maximum so far in the simulated day) is provided in the dashboard.

## Assigning Alternative Parking Sections When No Spot is Available in the Preferred Section as a Plane Arrives (for Advanced Users)

To select the alternative parking section, the researchers defined expressions for S1alt, S2alt, etc. In such expressions, if conditions in parentheses are true, the value of the condition was 1; otherwise, the value was 0. See Appendix A for names and descriptions of key variables and expressions.

First, the t2ratiomax was defined to be the maximum ratio of S5ratio to be the ratio of assigned parking spots in Section 5 to the usable spots in Section 1. It is expressed as a percentage, which may exceed 100% if t2ratiomax exceeds 100% (possibly in anticipation that a gate may become free as the plane taxis inbound or to accept some wait instead of going to a lesser preferred parking area).

A sample reassignment rule is as follows:

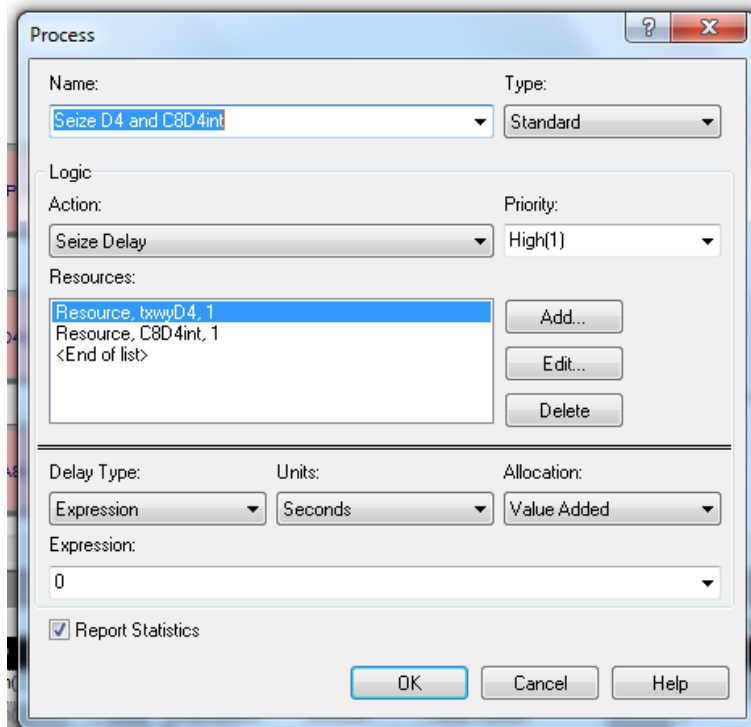
$$(t2ratio < t2ratiomax) * ( 5*(s5ratio <= s6ratio)*(s5ratio <= s7ratio) + 7*(s7ratio <= s5ratio)*(s7ratio < s6ratio) + 6*(s6ratio < s7ratio)*(s6ratio <= s5ratio) ) + 4*(t2ratio >= t2ratiomax)$$

This causes planes with preferred Parking Section 5 to be diverted to the least occupied section (5, 6, or 7) in Terminal 2 if Terminal 2 gate assignments (including planes taxiing inbound) do not exceed the maximum allowed by t2ratiomax. Otherwise planes are diverted to Parking Section 4. This balances usage of parking sections in a terminal but without consideration of airline preferences for specific gates.

### **Changing ATC Rules for Handling Traffic (for Advanced Users)**

Embedded in the flow logic are requests for resources that are shared by airplanes. These requests may occur with different priority levels (as needed to allow landing aircraft to have priority over planes on the ground when there are multiple requests for a runway). Numbers or expressions may be used to request a resource with higher priority (where small numbers indicate higher priority). Other situations where priorities may be used are at intersections in the taxiway network (which usually have capacity = 1 plane).

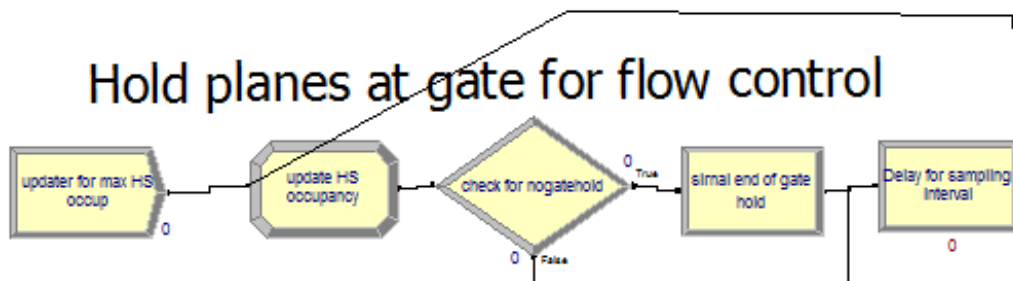
To alter priorities in this fashion, the user should consider all “seize” or “process” blocks for the relevant resource (see Figure 17).



**Figure 17. Altering priorities for traffic handling**

### Imposing Gate Holds as a Flight Flow-Control Mechanism

An artificial entity is used to check the status of airport operations at a chosen time interval and to place holds on aircraft requesting pushbacks under specified conditions. It also sends a signal to release a designated number of planes (1 by default) when conditions allow (see Figure 18).



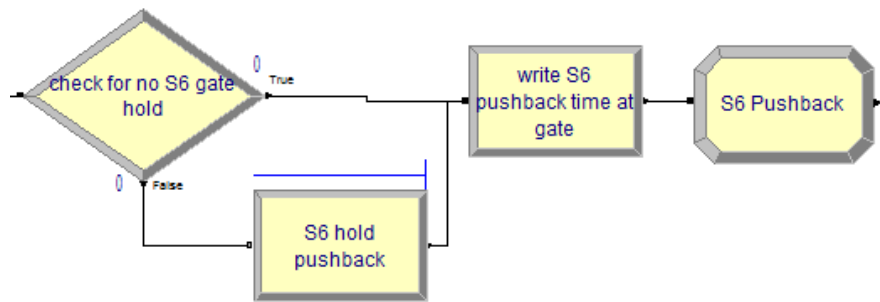
**Figure 18. Checking status of airport operations and placing holds on aircraft pushback**

By adjusting the rules for assigning the “nogatehold” variable, the user may control the release of aircraft and limit the number that would be taxiing outbound at the same time. This is the current practice wisely used by ATC to avoid unnecessary fuel burn and air pollution from planes held on taxiways with their engines running. To impose the holds based on the count of planes taxiing out, an expression like the following is used:

$$\text{Nogatehold} == 1 * (\text{taxiingout} < 10) + 0 * (\text{taxiingout} \geq 10)$$

This expression imposes gate holds for planes ready to depart from a section if 10 or more planes are taxiing out when the plane is ready to depart from its gate.

Planes held for pushback from all sections are held in a single queue for “outbound release.” The “hold planes at gate” condition in the module above is checked at specific time intervals (e.g., 60 seconds) so that it would be possible that occasional simultaneous requests for pushback could cause a momentary release of additional planes. To protect against this, the “taxiing out” limit was also included in the following logical block for “outbound release” of aircraft (Figure 19).



**Figure 19. Module regulating outbound release of aircraft**

At current traffic levels, there are just a few times of the day when this would be a momentary issue. Using similar techniques, the analyst can delay inbound flights to simulate disruptions, which delays arrivals and creates bunching of inbound traffic.

The general “gate hold” feature may be suppressed by changing the “first creation time” for the “updater for max HS occup” entity to a larger number (e.g., 99999) instead of 0. With that suppression, the related departure delays would be reduced, planes would be released, and they would have to wait on taxiways as others depart ahead of them. Their gates, however, would become available for arriving aircraft. Advanced users could alter the assignment of the “nogatehold” variable to consider more complex rules depending on planes taxiing inbound and outbound.

## **SUMMARY OF USER-ADJUSTABLE PARAMETERS**

Arena offers extensive interactive documentation of the variables that it uses to represent the system and control the simulation process (Kelton 2009). The “build expression” feature has dropdown menus that allow the user to select them using their generic meanings. The name of the corresponding variable, expression, or attribute is substituted when the variable is selected (by clicking on the chosen item). The run-control command window also has a dropdown menu that presents many of them in context if a user wishes to “show” their values at an interrupted point in the simulation process. In Appendix A, the researchers define the “user-defined” parameters and expressions that may typically be reset by users to experiment with different scenarios. Variables and expressions that are used in statistical models for arrival and departure delays are also defined.

## SAMPLE INSIGHTS FROM SIMULATION RESULTS

To examine airport capacity and apparent constraints at different stages of growth, the researchers simulated schedules with increases of 20%, 40%, 60%, and 80% relative to the base case. Scheduled activity in the experimental environment varied throughout the day, as illustrated in Figure 20.

hour	Flights	NE Flights	SE Flights	SW Flights	NW Flights	Arr	Dep
0	6	0	0	5	1	4	2
1	9	1	0	4	4	9	0
2	9	2	1	4	2	9	0
3	2	0	0	0	2	1	1
6	10	2	1	4	3	0	10
7	22	3	2	12	5	2	20
8	24	9	1	12	2	7	17
9	32	5	2	16	9	22	10
10	32	8	2	18	4	14	18
11	35	10	0	20	5	20	15
12	35	12	2	16	5	17	18
13	35	7	1	17	10	19	16
14	40	9	4	19	8	18	22
15	33	11	3	16	3	17	16
16	36	7	0	16	13	18	18
17	33	12	0	17	4	16	17
18	32	8	1	18	5	14	18
19	31	5	3	16	7	20	11
20	36	3	1	26	6	14	22
21	33	4	0	23	6	18	15
22	22	5	1	12	4	10	12
23	14	0	2	11	1	11	3
	<b>561</b>	<b>123</b>	<b>27</b>	<b>302</b>	<b>109</b>	<b>280</b>	<b>281</b>

**Figure 20. Scheduled daily flight activity**

Variations in arrival and turnaround times cause demands for traffic movements to intensify at some times and relax at others. As growth in traffic is stimulated, constraints are not explicitly imposed on the total number of flights per hour. However, the researchers do report the number of simulated flights in each hour so that analysts may see the extent to which the constraints on total flow would have to be relaxed to accommodate traffic growth.

## **Historical Delays and Taxi Times**

Examining historical statistics for taxi times, the researchers noticed remarkable consistency between busy periods and slack periods, which suggested an operating environment with more than sufficient airside capacity to accommodate current traffic levels. The data were symptomatic, however, of regulation in gate releases to prevent congestion in runways and taxiways with wasted fuel and exhaust emissions. Subsequent discussions with ATC confirmed these deductions, which caused the researchers to incorporate the “gate hold” provisions to mimic this practice. ATC attributed the higher delays in summer to weather, incoming delays, and higher passenger loadings with related groundside activity.

## **Deployment of Tractors for Pushbacks**

In the experimental environment, the airport maintenance department provides tractors for pushbacks of aircraft by most carriers. As the model was calibrated with initial deployments (default positions) and ranges of activities for tractors, the researchers noticed in the performance dashboard that there were some times when delays occurred while tractors were idle in other sections of the airport. Simulated delays were reduced substantially by changing the gates that could be supported by individual tractors. This effectively allowed idle tractors that served other gate groups to respond to the calls for pushback during peak periods. The model revealed potential opportunities to employ a “dynamic tractor assignment” scheme that could help to accommodate growth in traffic and to increase the utilization of tractors as demands for pushbacks shifted around the airport. Figure 21 shows the effects of altering tractor deployments accordingly. Later discussions with maintenance representatives confirmed that model assessments of tractor needs agreed with their own assessments and operating practice.

Hour of Tractor Request	No. of Tractors Engaged	Av. Wait (Min.)	Percent Engaged After Wait > 5 Min.
7	1	0.0	0.0
9	11	6.6	36.4
10	9	0.0	0.0
11	14	3.1	35.7
12	9	0.0	0.0
13	13	5.5	30.8
14	8	11.3	62.5
15	11	12.4	81.8
16	14	10.1	64.3
17	11	1.4	18.2
18	10	4.3	50.0
19	10	0.0	0.0
20	14	4.0	42.9
21	7	3.4	42.9
22	9	6.4	55.6
23	11	1.6	9.1
	162		

Hour of Tractor Request	No. of Tractors Engaged	Av. Wait (Min.)	Percent Engaged After Wait > 5 Min.
7	1	0.0	0.0
9	11	5.1	36.4
10	9	0.0	0.0
11	14	2.9	21.4
12	8	0.0	0.0
13	13	1.4	7.7
14	9	2.2	11.1
16	11	2.8	36.4
18	13	1.4	15.4
17	12	0.0	0.0
18	10	0.0	0.0
19	10	0.0	0.0
20	14	1.0	7.1
21	7	0.0	0.0
22	10	1.7	20.0
23	10	1.5	10.0
	162		

**Figure 21. Pushback delays while waiting for tractors: with original tractor deployment (left) and with adjusted tractor deployment (right)**

### ATC Separation Standards for Approaches and Departures

Considering direct observations at several international airports, the researchers set 1 minute as the separation standard between successive departures from the same runway, but this could, of course, be changed and set to consider the sizes of the aircraft in successive departures. The researchers also used a minimum of 1 minute separation for approaches assuming a ground speed of 140 knots (net of headwinds) from the final approach fix to touchdown for each runway.

ATC at the test facility generally held a departure if an arriving aircraft was within 4 km of touchdown on the parallel runway. As mentioned above, the simulation model has a “holdparallel” parameter that allows this option to be turned on (= 1) or off (= 0). The results in this report are based on holdparallel =1 (on).

As traffic grows, ATC could consider the effects of more flexibility in runway usage, altering separation standards for departures, and the “holdparallel” requirement.

### Runway Usage

In Appendix B, the results of applying the simulation model are shown for scenarios involving the following:

- Landing RWY 25 departing RWY 24



- Landing RWY 24 departing RWY 25
- Landing RWY 25 with mixed departures on RWY 24 and RWY 25
- Departing on RWY 24 from Parking Sections 1, 2, 3, 4, 6, 8, and 9
- Departing on RWY 25 from Parking Sections 5 and 7

All of these scenarios apply to the situation where winds are from the southwest. The choice of runways for operations has a considerable effect on taxiing times of aircraft to and from their assigned gates. The following chapter describes the mechanics of achieving such results.

## STEPS FOR RUNNING THE ARENA SIMULATION MODEL AND SAS REPORT GENERATOR

1. Click on *Program name.doe* to open the Arena model or use *File > Open > Program name.doe* from an active Arena window to open the program.
2. Use *Basic Process > Variable* to set the variable *winddir* to “NE” (to use RWY 07 and RWY 06) or “SW” (to use RWY 25 and RWY 24).
3. Use *Advanced Process > Expression* to set expression for *arrivrwyindicator* to set the index for the desired runway for arrivals (1 = RWY 24, 2 = RWY 25, 3 = RWY 06, 4 = RWY 07, or the name of a chosen expression for mixed use).
4. Use *Advanced Process > Expression* to set expression for *deprwyindicator* to set the index for the desired runway for departures (1 = RWY 24, 2 = RWY 25, 3 = RWY 06, 4 = RWY 07, or the name of a chosen expression for mixed use).
5. Click on the Run wedge (or use *Run > Go*) to run the model (see Figure 22).



Figure 22. Run wedge button

6. To stop the model at the end of the run and change setups, click on the Stop Run square (see Figure 23).



Figure 23. Stop Run button

7. To run the animated model and stop it at a particular time of day (e.g., 2 pm = 14:00, or 6\*14 = 840 minutes after midnight) and examine the dashboard, use *run > run control > command* to produce a command window and enter the command “go until 840” and observe the dashboards (illustrated earlier) that result by hitting the “d” key (see Figure 24).

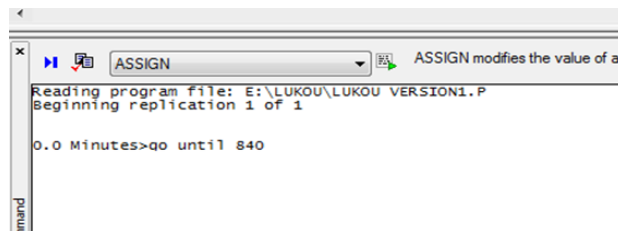


Figure 24. Stopping to examine the dashboard at a particular time of day

The user may also examine the status of queues at a point in simulated time by moving the cursor in the model template to the relevant section of the animated logic, as illustrated next (see Figure 25). Be sure that there is a proper balance of inbound and outbound flights. If

there is an imbalance, the bottleneck or deadlock should be revealed by a queue at some point in the model.

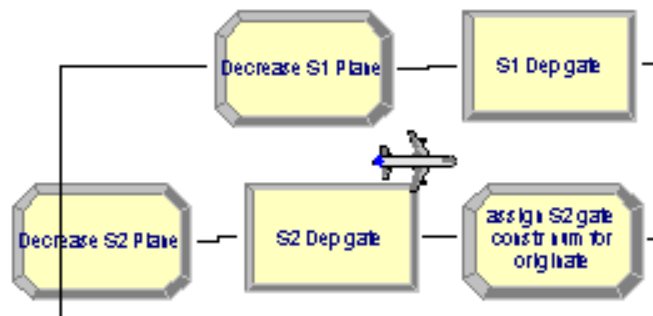



Figure 25. Animated status of queues

8. Use *File > open > Report program name.SAS* to open the reporting program.
9. Reset macro names for the chosen scenario (last statement of a macro is the active version):
 

```

      %macro eventlog; "e:\airport\eventlog08222016LDG07DEP06i00pct.txt" %mend;
      %macro tractorlog; "e:\airport\tractorlog08222016LDG07DEP06i00pct.txt" %mend;
      %macro tracklogpdf; "e:\airport\APT 20160822simulated flights by aircraft LDG07DEP06
      i00pct.pdf" %mend;
      %macro scenario; title2 simulated APT Aug 22 2016 Schedule LDG07 and DEP06 i00pct;
      %mend;
      %macro taxitimespdf; "e:\airport\APT 20160822 simulated Taxi Times for LDG07 DEP06
      i00pct.pdf" %mend;
      %macro listing; "e:\Airport\APT 20160822 simulated LDG07 and DEP06 i00pct.pdf"
      %mend;
      
```
10. Run the SAS program (  ) to generate the three pdf files with reports of the simulation results.
11. Examine the statistics in the three reports that result:
  - v1APT 20160822 simulated LDG07 and DEP06 i00pct.pdf
  - v1APT 20160822simulated flights by aircraft LDG07DEP06 i00pct.pdf
  - v1APT 20160822simulated flights by aircraft LDG07DEP06 i00pct.pdf

## CONCLUSION

In the experimental environment, personnel from each of the three areas (AOC, maintenance, and ATC) worked closely with the researchers to ensure that the model properly represented airside activity. Following an intensive week in which representatives from each department closely examined simulated activity and offered final suggestions for fine-tuning the model elements and parameters, each of the three departments agreed that the simulation model was generating appropriate information for their collaborative efforts in maximizing airport performance with objective data-driven decision support.

The model facilitated discussion of ways that flexible use of runways may offer opportunities to reduce taxi times, fuel burned, air pollution, and propagated delays experienced by airlines downstream. Further exploration of this potential in the experimental environment requires careful consideration of managing congestion that can occur in Hotspot 3 at the approach end of RWY 25.

The researchers envision the model as a useful tool for programs of continuous improvement in an airport's airside operations. Applications of the model can help to determine where and when activity will be concentrated for people and airplanes and how best to utilize new resources. This may be accomplished through a virtuous cycle involving the following:

Modeling > Validation > Experimentation > Change > Assessment

Immediate applications pertain to the following:

- Times for new flights in the schedule
- Preferred parking sections (gate pre-assignments) for flights in the schedule
- Rules for re-assignment of parking sections when arriving aircraft face congestion or completely occupied gates in their preferred parking sections
- Needs for tractors, tractor positioning, tractor failures, range of activity, and repositioning times
- Locations of new parking gates or parking stands to accommodate additional flights.

With continuing research, the researchers are studying the robustness of inferences from simulation results to alternative screens of data used to calibrate the models.

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## APPENDIX A. USER-DEFINED VARIABLES AND EXPRESSIONS

**Table A.1. Variables used to create simulation scenarios or employed in the embedded statistical models**

Variable Name	Variable Definition	Purpose
winddir	Direction from which the wind is coming	Determines appropriate runways to use by choosing “NE” or “SW”
schedhour	Hour of the day for a scheduled activity	Not changed by user but can be used in logical expressions
hour1-hour23	0–1 indicators of hour of day for current simulated time	Not changed by user but used in statistical models provided by user
nogatehold	No hold on planes at gate	Used to control outbound flow
noramphold	No hold for planes at staging points on ramp	Used in logic for outbound flow control
Tento4pm	0–1 indicator for time between 10 am and 4 pm	May be used in statistical models
After4pm	0–1 indicator for time after 4 pm	May be used in statistical models
Before10am	0–1 indicator for time before 10 am	May be used in statistical models
timeapp	Array with approach times from FAF	Controls time required to complete approach
landingroll	Time required for rollout on landing	
crossrwy	Time to taxi across a runway	Not used because of APT layout
cvtimes	Coefficient of variation for times with lognormal distributions	Allows experimentation with variation imposed on activity times
xramptogate	Time (sec.) to cross a ramp to gate	
intogate	Time (sec.) to taxi into gate from ramp	
turnaroundmin	Default minutes average for immediate turnaround	
stdevmultiple	Factor for scaling variability in times (default=1)	
schedturnaroundt	Scheduled time to turnaround a plane considering arrival time	May be used in statistical models for turnaround times
schedturnsq	Square of <i>schedturnaroundt</i>	May be used in statistical models
tugreleaseing	Av. time to release a tractor after pushback	
xramptodeppt	Av. Time (min.) to cross ramp to departure staging point	
txspdftpersec	Average taxi speed (ft/sec.)	

<b>Variable Name</b>	<b>Variable Definition</b>	<b>Purpose</b>
shortmovementssec	No. of seconds for short movements	
meaneqdelay	Mean time for equipment delays (min.)	Allows random deviation for equipment delays before departure
stdeveq	Std. dev. For equip delay (min.)	
avpbtime	Average time to push back plane	Time to complete pushback
Summer	0–1 indicator of summer month (July–September)	May be used in statistical models
Fall	0–1 indicator of Fall month (October–December)	May be used in statistical models
Winter	0–1 indicator of Winter month (April–June)	May be used in statistical models
Appspeed	Approach speed (knots)	When on short final
holdparallel	0–1 switch for invoking hold parallel constraint on takeoffs	Reduces number of takeoffs per time period when busy
randomparkingsection	0–1 switch for randomizing preferred parking section (except for China Post)	May be used to study effects of changes to infrastructure when preferred section is unknown for flights in the schedule
xintersectionsec	Time required for aircraft to cross an intersection and release it for the next aircraft	May be used to bring average unencumbered taxi times in alignment with historical data
Hs3limit	Maximum number of aircraft to be allowed in Hotspot 3	May be used in expressions that divert traffic from taking off on runway 25 to avoid congestion
T1ratiomax, T2ratiomax	Maximum proportionate usage allowed for T1 gates (may exceed 1.0)	Used in rules for parking section reassignments
Taxioutmax	Maximum number of planes allowed to be taxiing out at a point in time	Departure flow control



**Table A.2. User-defined expressions for controlling process flow**

<b>Expression Name</b>	<b>Expression Definition</b>	<b>Purpose</b>
sepappfix	Minimum number of minutes between release of planes from the final approach fix	Safety separation
probeqdelay	Probability of an equipment delay preventing pushback when plane is otherwise ready for departure	Delays of affected flights
meanpbtime	Average time required to push back an airplane after tractor is in position to push back the aircraft	Pushback times for affected flights
excessturnaroundtime	Expected residual time to turn around an aircraft beyond average	May be used to adjust turnaround times for variables not in the statistical models
pbresid	Random variable for adjusting turnaround time of originating flights	Used for unexplained (residual) variation in dep. delays of originating flights
pbresidC	Random variable for adjusting turnaround time of continuing flights	Used for unexplained (residual) variation in dep. delays of continuing flights
hourofday	Hour of day in simulated time (computed from Arena variable tnow)	
takeoffroll	Time for aircraft to lift off the runway after beginning its takeoff roll and before runway is freed	
wakeclearance	Minimum time required between takeoffs from the same runway	
arrivrwyindicator	Index of the arrival runway to be used for a flight	May use an expression to make the choice of runway depend on other variables
deptrwyindicator	Index of the departure runway to be used for a flight	
probdepdelayimmmturn	Probability of departure delay for an immediate turnaround (with < 31 min. to scheduled departure time)	Usually a logistical statistical model to make the probability depend on other variables
probdepdelaynonimmmturn	Probability of departure delay for nonimmediate turnaround (with > 30 min. to scheduled departure time)	Usually a logistical statistical model to make the probability depend on other variables

<b>Expression Name</b>	<b>Expression Definition</b>	<b>Purpose</b>
T1ratio, T2ratio	Proportion of parking spots (0–1) in Terminal 1 and Terminal 2 currently occupied or allocated to planes taxiing in	Used in decision rules for sending planes to alternative parking sections when spots in preferred section are occupied
S1alt-S7alt	Alternative parking sections to which planes are sent if respective parking sections are too full	Constitute decision rules used for choosing the alternative parking sections
connecttractortime <i>GxtoGy</i>	Probability distribution for time to acquire and connect a tractor in gate group <i>GxtoGy</i> if a tractor is not available when the plane is ready for pushback	Suggest a triangular distribution with min., most likely and max. times with consideration of normal positioning and range of activity of the tractors able to serve the gate group
Taxiingin, taxiingout	Number of planes currently taxiing in and out	Computed for dashboard display and for possible use in decision rules for flow control
Various indicators of the status of airport activity	See dropdown list of expressions and “find” then in the model logic	Used for dashboards and in decision rules for traffic flow
mixeddepsw	Index of runway to be used for a departure when wind is from the southwest	Build the expression to control which aircraft use which runway
mixedarrsw	Index of runway to be used for an arrival when wind is from the southwest	Build the expression to control which aircraft use which runway
pMUnneedstractor	Probability that a China Eastern flight will need a tractor if departing from a gate that requires pushback	
pZUnneedstractor	Probability that a Shenzhen flight will need a tractor if departing from a gate that requires pushback	
ZUorMUnneedstractor	Indicator that the departing aircraft is a Shenzhen or China Eastern that needs a tractor for pushback	
hs3aircraft	Current number of aircraft in Hotspot 3	For performance dashboard
MXhs3aircraft	Maximum number of aircraft that were simultaneously in Hotspot 3 so far this day	For performance dashboard

<b>Expression Name</b>	<b>Expression Definition</b>	<b>Purpose</b>
s1ratio-s7ratio	Proportion of parking spots (0–1) in respective parking sections currently occupied or allocated to planes taxiing in	Used in decision rules for sending planes to alternative parking sections when spots in preferred section are occupied
T1cap	Total number of usable gates in Terminal 1	Sum of T1 section capacities
T2cap	Total number of usable gates in Terminal 2	Sum of T2 section capacities
pftime	Computed pushback time	Random variable for pushback time
turntimeimmturn	Expected turnaround time for immediate turnaround	
expdepdelaynonimm	Expected departure delay if nonimmediate turnaround	
residualimmturn	Residual variation for immediate turnaround	
residualdelaynonimm	Residual delay for nonimmediate turn	
turntime	Computed time to turn aircraft for departure	Computed from systematic and residual variations in turn times and delays
Sectcap	Array of computed section capacities (from capacities of gate resources)	
Pctgatesocc	Computed percentage of gates occupied	For dashboard statistic

**Table A.3. Other variables used in model logic (not controlled exogenously)**

<b>Variable Name</b>	<b>Variable Definition</b>	<b>Values</b>
SRW0624	Indicator of directional flow on RWY 0624	1 = northbound, 2 = either or idle, 3 = southbound
SRW0725	Indicator of directional flow on RWY 0725	1=northbound, 2=either or idle, 3=southbound
SCwest, SA3 etc.	Indicator of directional flow on taxiway segments	1 = northbound, 2 = either or idle, 3 = southbound
deprwysub	Index for arrival runway	1 = 24, 2 = 25, 3 = 06, 4 = 07
arrwysub	Index for departure runway	1 = 24, 2 = 25, 3 = 06, 4 = 07
nextarrivaltime	Time of next arrival at FAF	
Availxxapp	Time at which RWYxx is available for an approach	
Sygateref	Section y gate index	Identify relevant gate in set for section y
Sigigate	Gate number for Section I gate	Reading gate number from cross reference file

**APPENDIX B. RESULTS OF APPLYING THE SIMULATION MODEL**

		Delays (av. min. delay)		Flights with Delay > 15 min.		Ramp and Taxi time
		Flights	Av. Delay	Number over 15 min.	P(>15 min.)	Av. Minutes
section	event					
Sect 1	2: Arrival	998	18.8	463	0.464	5.4
	4: Departure	800	29.4	430	0.538	13.9
Sect 2	2: Arrival	800	20.2	395	0.494	7.1
	4: Departure	700	22.7	353	0.504	11.8
Sect 3	2: Arrival	483	40.0	284	0.588	9.0
	4: Departure	400	22.1	211	0.528	7.9
Sect 4	2: Arrival	200	23.4	116	0.580	10.2
	4: Departure	200	13.6	80	0.400	5.5
Sect 5	2: Arrival	5,629	23.1	3,096	0.550	6.8
	4: Departure	5,750	35.3	3,959	0.689	18.5
Sect 6	2: Arrival	14,618	19.7	7,045	0.482	6.3
	4: Departure	14,597	28.8	7,831	0.536	18.0
Sect 7	2: Arrival	3,905	23.3	2,132	0.546	9.9
	4: Departure	4,205	42.1	2,964	0.705	21.5
China P	2: Arrival	1,000	14.8	374	0.374	9.1
	4: Departure	1,000	5.5	96	0.096	9.9
Overall		55,285	26.0	29829	0.540	12.5

**Figure B.1. Simulated performance statistics base case, 100 replications, landing RWY 25 and departing RWY 24**

		Delays (av. min. delay)		Flights with Delay > 15 min.		Ramp and Taxi time
		Flights	Av. Delay	Number over 15 min.	P(>15 min.)	Av. Minutes
section	event					
Sect 1	2: Arrival	998	17.9	443	0.444	5.2
	4: Departure	800	28.4	430	0.538	10.9
Sect 2	2: Arrival	800	17.2	349	0.436	3.8
	4: Departure	700	20.6	331	0.473	11.8
Sect 3	2: Arrival	492	37.0	268	0.545	4.2
	4: Departure	400	20.7	195	0.488	12.4
Sect 4	2: Arrival	200	19.0	99	0.495	5.4
	4: Departure	200	13.4	79	0.395	13.6
Sect 5	2: Arrival	5,687	24.2	3,246	0.571	9.2
	4: Departure	5,817	35.0	3,974	0.683	8.8
Sect 6	2: Arrival	14,552	20.4	7,245	0.498	8.6
	4: Departure	14,578	28.6	7,701	0.528	10.5
Sect 7	2: Arrival	3,890	24.2	2,193	0.564	12.1
	4: Departure	4,188	42.8	2,938	0.702	10.3
China P	2: Arrival	1,000	11.7	306	0.306	4.6
	4: Departure	1,000	5.1	94	0.094	10.9
Overall		55,302	26.2	29891	0.541	9.5

**Figure B.2. Simulated performance statistics base case, 100 replications, landing RWY 24 and departing RWY 25**

		Delays (av. min. delay)		Flights with Delay > 15 min.		Ramp and Taxi time
		Flights	Av. Delay	Number over 15 min.	P(>15 min.)	Av. Minutes
section	event					
Sect 1	2: Arrival	997	18.3	450	0.451	5.3
	4: Departure	800	29.4	430	0.538	13.9
Sect 2	2: Arrival	800	17.6	352	0.440	3.8
	4: Departure	700	21.6	336	0.480	12.0
Sect 3	2: Arrival	491	37.3	271	0.552	4.3
	4: Departure	400	21.2	202	0.505	7.8
Sect 4	2: Arrival	200	19.5	102	0.510	5.5
Sect 5	2: Arrival	5,673	24.8	3,305	0.583	9.4
	4: Departure	5,803	36.4	4,064	0.700	9.4
Sect 6	2: Arrival	14,578	20.8	7,369	0.505	8.7
	4: Departure	14,558	29.3	7,921	0.544	18.2
Sect 7	2: Arrival	3,875	24.7	2,212	0.571	12.2
	4: Departure	4,178	43.4	2,993	0.716	9.4
China P	2: Arrival	1,000	11.7	307	0.307	4.6
	4: Departure	1,000	5.1	94	0.094	9.9
Overall		55,053	26.8	30408	0.552	11.5

**Figure B.3. Simulated performance statistics base case, 100 replications, landing RWY 24 and departing RWY 24 and RWY 25**







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