Intelligent Decision Support for Aircraft Logistics at Commercial Airports

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Abstract

For airline traffic at major commercial airports, systems of staged queues are employed to coordinate flight and ground operations of independent carriers with some competing and some collective interests. System performance is affected by the concentration of airlines' flight schedules, resources allocated for gate operations, taxiway and ramp layouts, air traffic control procedures for aircraft on the ground and in the air, adverse weather conditions, traffic backups at major connecting hubs, etc. We present a conceptual framework and discrete-event simulation model for examining how changes in airport design, ground resources, operating procedures and sequencing techniques for traffic movements affect different stakeholders.

1. Introduction

Airline operations at commercial airports occur within a tightly coordinated system geared to ensure safe operations as individual carriers strive to adhere to their published schedules. Flight activity is often concentrated in periods of peak passenger demand and interruptions may occur with adverse weather and equipment failure. At some airports, express freight carriers, corporate aircraft and private aircraft add significantly to the traffic mix. Air traffic controllers synchronize approaches, departures and ground movements to maintain proper separation of aircraft while trying to make best use of airport resources considering the prevailing conditions. The ease and efficiency with which operations occur depends on the physical configuration of runways, taxiways, ramps and gates. They also depend on the resources (gates, equipment and personnel) that airlines deploy and the airlines' own dispatching processes.

Economic effects are realized through capital and maintenance costs for the airport infrastructure, fuel consumed by aircraft, expenditures for flight and ground personnel, and indirectly as passengers experience flight delays, missed connections, etc. Environmental impacts are felt in the form of noise and air pollution. Needed for intelligent strategic and tactical planning at commercial airports are analytical tools that can help airport stakeholders investigate the effects of:

- Altering airport taxiways, ramps and their designated uses to improve safety or operational efficiency
- Changing gate allocations and the supporting personnel and equipment for individual carriers
- Introducing flexibility in the use of gates and supporting equipment between cooperating airlines
- Changing the usage of runways for arrivals and departures under various weather and traffic conditions
- Alternative ways of staging aircraft for final approach, arrivals at gates, dispatching to active runways, and flight departures (considering traffic and weather conditions in airspace sectors and times involved in synchronizing traffic movements on the ground)
- Changing flight schedules and the intensity of traffic throughout the day.

We present, in this paper, an analytical framework and discrete-event simulation model which, with embedded optimizing heuristics, can help airport planners to address these issues. The airport environment is represented as a network of staged queues and discrete-event simulation is used to represent system behavior. With our methodology, we can:

- Integrate multiple activities under different spheres of control with interacting effects
- Represent the system without excessive granularity while considering essential operating characteristics
- Incorporate stochastic variation caused by systematic variation in the intensity of scheduled flight operations at different times of the day, day of the week, and time of the year
- Allow for random events that impair normal operations (weather, traffic delays at connecting hubs)
- Assess the time-varying and differential effects of changes in infrastructure and operating practice upon individual stakeholders (individual airlines, aircraft type or class of carrier).

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2. Related Research

Airport and airspace planners for decades have used discrete-event simulation for studying system capacity in the air and on the ground. The airport and airspace modeling tool, SIMMOD, created in Simscript for the United States Federal Aviation Administration (FAA, 1989), has been used worldwide to estimate airport runway and terminal capacities (Gilbo, 1993, Fishburn et al.,1995; Wei and Siyuan, 2010; Bobalo and Daduna, 2011). It has also been used to study specific airport operations such as de-icing services during snowstorms (Bertino and Boyajian, 2011). SIMMOD represents airspace and airports as two-dimensional networks of activity where entities move among nodes in the network along links which can be tailored to the special characteristics of the aircraft and their environments (e.g., allowing or restricting passing on taxiways and enforcing separation standards in the air that depend on the size of aircraft). Additional realism in representing altitude is achieved in the widely used Total Airpace and Airport Modeller (TAAM) developed by a Boeing subsidiary (see Offerman, 2001; Odoni et al., 1997). These simulators (SIMMOD and TAAM) provide very realistic depictions and visualizations of simulated aircraft movements from gate to runway to destination with consideration of all traffic, individual aircraft characteristics, separation requirements, wind and weather conditions and detailed flight plans. They are excellent resources for observing detailed aircraft movements and testing the feasibility of simulated aircraft activity under particular scenarios in a specific time period with microscopic detail, but they carry a great deal of overhead for studies with a more strategic focus.

Various modeling approaches and techniques have been used for studying aspects of airport operations in support of strategic planning. Norin et al. (2009) describe the interplay of airline operations, air traffic control, and airport operations and the various commercial simulation packages available for modeling and analysis of “airside operations”. They illustrate the use of a mathematical programming model for scheduling de-icing operations and integrating it into a simulation model for airport ground operations. For passenger services in and around the airport terminal, Snowdon et al. (2000) use ARENA to simulate the movement of passengers and baggage through ticketing, check-in, boarding and loading. Horstmeier and de Haan (2001) used an ARENA model to simulate functions in turning around the Airbus A380 and found opportunities to reduce times by changing aircraft configurations and processes for food catering and passenger disembarkation. To pursue “optimal” solutions for a broader aspect of gate activity (the assignment of aircraft to gates) and test them in a stochastic environment, Yan et al. (2002) employ a mathematical programming model, heuristics and rudimentary simulation using Fortran 90 to consider stochastic effects. Ravizza et al. (2013) present an algorithm that determines optimal taxi routes (and sequences of movements) for repositioning aircraft (as with arrivals and departures) with consideration of fuel time required to complete all scheduled movements. Zografos and Midas (2006) discuss how collections of models with individual strengths, harmonized databases of relevant information, and domain-specific analytical tools can be integrated with the help of a human-machine interface to serve as a decision support system (DSS) for airport planning and performance studies.

In the air traffic control system, arrivals are sequenced dynamically by air traffic controllers who stage arrivals as necessary at holding points and funnel them through final approach fixes for the active runways, generally using the first-come first-served (FCFS) principle but with some adjustments to adjust for current pressure on the system. The airspace planning models and studies go to great lengths to consider the detailed interplay of aviation activities and adjust for the effects of individual aircraft characteristics and conditions when determining the times and delays associated with aircraft movements. They generally operate on a FCFS basis relative to schedule (as when pushing back from gates) or when approaching a node in the simulated network (e.g., at an arrival fix or a departure runway). Doing so, the models emulate the behavior of airline dispatchers and air traffic controllers to the extent possible (though with less flexibility). They adjust the times and flight paths to enforce aircraft separation standards.

Research on scheduling in job-shop environments has shown that efficiencies can often be achieved by deviating from FCFS processing order (Allahverdi et al., 1999, 2008). Integer programming (IP) models and heuristic solution procedures have been employed for scheduling jobs where setup times depend on job sequences (Balas et al., 2008; Carroll & Bronzini, 1973; Dai & Schonfeld, 1998; Gagné et al., 2002; Gendreau et al., 2001; Gupta & Smith, 2006).

Atkin et al. (2009) sought improvements relative to a FCFS departure sequence for departures at London Heathrow airport by staging aircraft in different patterns at the holding area for the departure runway. Solutions were developed mathematically using tabu search with random generation of alternative sequences for test solutions. They examined the relative effects of constraints for physical separation of aircraft during liftoff, along routes prescribed for standard instrument departures (SIDs) and while maneuvering through the holding area. Dealing with the complementary problem (arrival sequencing), Brentnall and Cheng, used discrete-event simulation to study the effects of using rules other than FCFS for sequencing aircraft approaches to a commercial airport and concluded that the benefits are not significant if the sole concern is runway capacity for arrivals. Atkin et al. (2010) reviewed past work on optimizing aspects of airport ground operations, recognized the prevalence of MIP formulations and the need for heuristic methods for practical purposes; they underscored the importance of integrating the essential elements of arrival sequencing, departure sequencing, gate assignments and ground movements when analyzing the problem.

In a different transportation context, Smith et al. (2011) showed that a heuristic scheduling procedure for staged queues (with priority-shifting mechanisms to ensure equity) could be used to improve performance over FCFS at locks in a river transportation system. Staged queues have the characteristic of one or more members' being designated as ready to be selected for service and therefore being in a subset that may be removed next from the queue when a resource becomes available or a signal occurs. This attribute has particular relevance in transportation and logistics, as physical restrictions often limit the mobility of queued entities. In the waterway environment, improved efficiency overall could be realized without imposing great hardship on any class of vessel. Depending on the tightness of the time intervals at which priority shifting occurs, the burden of delays, however, shifted from one class of user to another.

Our present conceptual framework and modeling approach are designed to facilitate the study of different sequencing methods for aircraft activity while recognizing the control exercised by the main parties in the system. The model provides a convenient tool for exploring the effects of changes to the airport's physical infrastructure, supporting equipment, personnel and operating practices in each domain. We illustrate its application to the Lambert St. Louis International Airport.

3. Staged Queues as the Integrating Framework

We integrate the three domains (airline operations, airport facilities and air traffic control) by moving simulated aircraft through a network of staged queues – some physical, others conceptual.

Aircraft arrivals are generated according to daily schedules of individual airlines but with random deviations appropriate for the scenario being simulated. The scenario is defined by local weather conditions, weather in airspace sectors through which arrivals and departures take place, and conditions at major hub airports which may cause bunching of arrivals and traffic holds for departures. Departing aircraft for flights that originate at the airport are generated according to schedule, "positioned" at an available gate for the airline (assuming that equipment is available) and designated as ready for departure with random variation that reflects historical deviations for the time of day, individual airline and flight destination. Departures for continuing flights occur after a random interval for "turnaround" at the gate.

Physical movements of aircraft are represented (and animated crudely for demonstration purposes only) as movements between "stations" along "routes". Sequencing and separation are subject to rules that consider the class of individual aircraft (heavy, medium, light). Figure 1 shows the final approach fixes (FAFs) at which aircraft are positioned as they enter the animated portion of the simulation model depending on the active runways. Aircraft in queues at the FAFs have attributes (aircraft type, scheduled arrival time, ETA at the FAF, airline, flight number, flight origin, flight terminus).

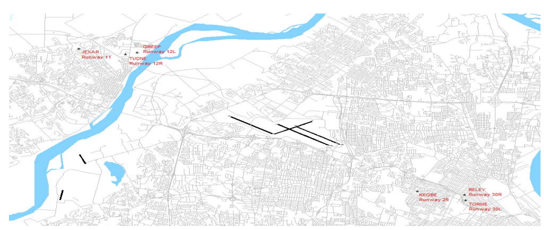

Figure 1: Final Approach Fixes for Staging Flight Arrivals

Flights that terminate at the airport are removed from the simulation and the gate is vacated after an interval for unloading and servicing. That makes the gate available for originating flights that are generated by the model according to schedule (with random perturbation if desired) or for a new arrival. If the flight is scheduled to proceed to a further destination, it becomes ready for departure after a turnaround time with a lognormal random component. Figure 2 illustrates the physical layout of runways, taxiways and ramp areas with key intersections that aircraft traverse from the points of touchdown to the gates and from the gates to the points of liftoff. Aircraft are released to traverse a segment of a taxiway no earlier than would allow it to reach the end before it is vacated by an aircraft ahead moving in the same direction. Nor can they enter a segment of a taxiway earlier than when it would be vacated by an aircraft currently traversing it in the opposite direction.

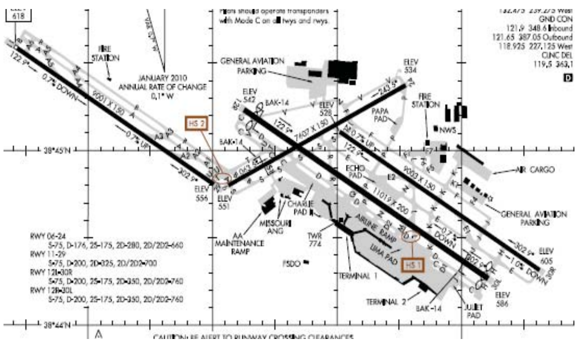

Figure 2: Airport Layout with Runways, Taxiways, Ramps and Key Intersections

Ramp areas are designated to accommodate staged queues when arriving aircraft do not have an available gate or a clear path to the assigned gate. At other points on the airfield, staged queues are used for departures when there is a backlog for takeoffs caused by congestion on the field , traffic holds due to weather conditions in departure sectors or holds due to weather or congestion at hub destinations.

To accommodate airlines' behavior in managing their own resources on the ground and dispatching their flights, we need to separate their activities for ramp and gate operations. This is done by designating separate staging areas on the ramp for each airline's arrivals and departures (Figure3). The airline's arriving aircraft are staged in queues in one area of the ramp pending the availability of a gate (and clear path to it). Departing aircraft (which may be held on the ground by ATC for weather or traffic control) are staged at another area if they must clear a gate to accommodate arriving aircraft. Figure 3 shows the gate staging areas and taxiing routes to the gates for four major airlines with gates at Terminal 1. Similar provision is made for arrivals and departures at Terminal 2. Other areas on the airfield are designated for spillover when physical capacity is reached at the designated ramp locations for staging the airlines' arrivals and departures.

In addition to the staged queues that are associated with physical positions on the airport property, aircraft are placed in conceptual queues that are shared by all airlines. Aircraft whose routes involve sectors of airspace temporarily restricted by severe weather, for example, are held in a common queue and released in sequences determined by the simulated scheduling regime in effect.

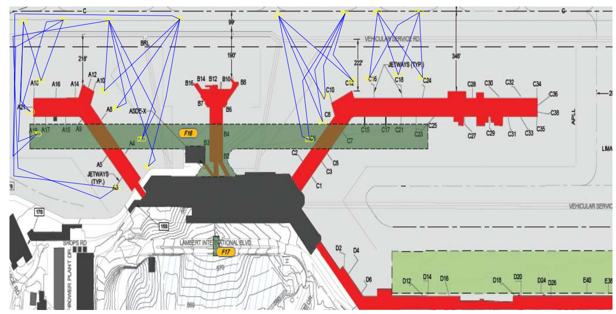

Figure 3: Staging Points on Ramps for Arrivals and Departures of Individual Airlines

4. Modeling tools

For the discrete-event simulation, we use ARENA 12.0 on a Windows platform. Heuristic scheduling and sequencing procedures are able to be written in C++ or Visual Basic and called by "event" blocks when the modeling logic requires them. The simulation is run in replicating mode (suppressing animation) to allow statistical tests of the effects of factors or strategies covered in the experimental scenarios. Adverse weather conditions in airspace sectors and at hub airports that affect traffic movements into and out of the local airspace are simulated by blocking aircraft from entering designated sectors (using either user-defined schedules or exponential probability distributions for successive events and their duration) and placing affected aircraft in queues for orderly release when the traffic restrictions expire.

Entity-specific and time-specific parameters for the simulation model are incorporated as logistic and regression models which are developed and maintained by the Statistical Analysis System (SAS) and embedded into the ARENA model. SAS is also used to generate files of arrivals for individual airlines (with some flights terminating and others continuing after turnaround at the gate) in conformity with historical airline schedules (intensified or thinned as desired to represent potential changes in traffic). It is used similarly to generate a file of originating flights for the simulated scenario. Randomness in arrivals and departures are imposed as normal deviations from schedule with daily and hourly time-varying means and standard deviations determined from historical airline gate data.

5. Information Generated

Airport activity varies throughout the day, with a tendency for flights to concentrate in popular times (Table 1). Delays propagate through the schedules as the day progresses. Some delays (such as weather) are highly correlated among carriers depending on schedules and routes flown (in our case, represented by airspace sectors and major connecting hubs). Others (such as equipment failure) are random. A comprehensive simulation model for airport operations must produce information in a form that allows one to investigate the dynamic performance of the system. For reporting of simulation results, we create detailed logs of simulated activity (written by Arena to flat files) and perform the analysis with SAS. Table 2 illustrates information that is saved by Arena for individual aircraft. Separating the simulation and analysis in this fashion, we can use data from multiple replications to investigate thoroughly how system performance varies through time. We can also assess the differential effects that physical or operational changes have on individual airlines or types of aircraft and estimate the extent to which variation is attributable to systematic versus random effects. With similar recording of information as planes leave or arrive at key queuing points, we can retrospectively deduce the state of the system at any point in simulated time (e.g., gates in use, queues at various stages for arriving and departing flights, simulated aircraft in motion on the ground, aircraft holding on a ramp or taxiway, and aircraft in the simulated airspace).

Table 1 - Actual Flights and Delays over 364 Days

Scheduled Flights and Delays		Airline					
		American	Delta	United	US Air	Southwest	Overall
Flights	Hour of Day						
	6AM to 8AM	2,284	1,557	1,179	1,430	3,168	9,618
	8AM to 10AM	2,165	1,005	1,166	1,031	5,144	10,511
	10AM to 12PM	2,387	742	913	325	4,100	8,467
	12PM to 2PM	2,608	458	928	673	4,080	8,747
	2PM to 4PM	2,272	787	893	666	3,663	8,281
	4PM to 6PM	2,629	1,045	1,641	1,024	3,722	10,061
	6PM to 8PM	2,030	699	1,560	317	4,684	9,290
	8PM to 10PM	1,046	24	38	134	3,626	4,868
	After 10PM	10	21	.	.	16	47
	Overall	17,431	6,338	8,318	5,600	32,203	69,890
Av. Delay	Hour of Day						
	6AM to 8AM	3.6	7.2	6.7	6.6	1.2	4.2
	8AM to 10AM	4.2	8.9	10.7	10.4	3.4	5.6
	10AM to 12PM	6.0	11.2	11.2	15.9	4.8	6.8
	12PM to 2PM	6.5	10.3	20.8	15.0	6.9	9.1
	2PM to 4PM	5.9	9.9	21.2	8.2	11.2	10.5
	4PM to 6PM	11.0	16.1	27.3	11.6	13.5	15.2
	6PM to 8PM	10.7	12.0	29.0	12.4	17.6	17.4
	8PM to 10PM	1.3	35.7	10.8	4.5	23.1	17.9
	After 10PM	14.4	20.6	.	.	12.5	16.5
	Overall	6.6	10.7	19.2	10.2	10.1	10.4

Table 2 Excerpt from a Simulation Event Log for Aircraft Activity

Obs	Replic. No.	Event time	Event	Airline	Flight Number	Lambert Gate	City	Continuing	Next City	Next Departure Time
192	1	0909	2: Arrival	WN	4215	E18	MDW	Yes	TUL	0935
193	1	0909	1: Touchdown	US	3599		PHL	No	N/A	N/A
194	1	0910	2: Arrival	WN	683	E20	CMH	Yes	OKC	0930
195	1	0910	5: Liftoff	AA	2217	C6	DFW	No	N/A	N/A
196	1	0911	2: Arrival	WN	280	E22	DTW	Yes	LIT	0935
197	1	0913	4: Pushback	WN	500	E4	MSY	Yes	N/A	N/A

Table 3 illustrates measures of system performance produced in a scenario to test the potential effects of gate holds and ramp holds imposed in St. Louis for flights destined to Chicago airports because of severe weather. Affected by the hold in this scenario were flights to ORD for American and United Airlines and flights to MDW for Southwest Airlines. As ramp and taxiway capacities allowed, flights to other destinations were permitted to continue. Delays, incidentally, are calculated as deviations from scheduled pushback rather than liftoff. The staged queuing strategy to cope with traffic holds can thus have a significant impact on actual and reported performance for an airline. Moving an aircraft to free a gate may make it possible for an airline to accommodate incoming traffic without interruption and enable an "on-time" departure, but it may also create congestion elsewhere on the ground that interferes with other departures. Strategies for dealing with weather interruptions are employed by both airline operations and air traffic control. Our modeling framework readily allows an exploration of alternative actions from individual airlines, on one hand, and from ATC ground control on the other hand. Requests for clearance (pushback) are initiated by the airline.

Table 3 – Simulated System Performance with Severe Weather at a Major Connecting Hub

		Delay (minutes)		Flights with Pushback Delay		Ramp and Taxi time
		Daily Flights	Av. Delay	Number	P(>20 min.)	Av. Minutes
airline	event					
American	2: Arrival	30	7.2	0	0.000	7.2
	4: Departure	36	8.3	2	0.056	8.8
Delta	2: Arrival	18	7.0	0	0.000	7.0
	4: Departure	19	0.0	0	0.000	7.6
United	2: Arrival	25	7.0	0	0.000	7.0
	4: Departure	33	6.4	2	0.061	15.3
US Air	2: Arrival	15	6.8	0	0.000	6.8
	4: Departure	16	0.0	0	0.000	7.7
Southwest	2: Arrival	79	7.5	0	0.000	7.5
	4: Departure	79	0.6	1	0.013	8.9
Overall		350	5.0	5	0.014	8.6

Such requests are granted and taxi directions are issued by air-traffic ground controllers. The model is structured so that the activities and decisions of individual airlines are represented by the times at which departing flights are "positioned" at the gates as ready for departure. The decisions of ground controllers are represented by the choice of active runways and taxi routes for arriving and departing aircraft and by dynamic priorities that are assigned to individual aircraft in the staged queues.

Table 4 contains the simulated results for the same weather scenario but a different strategy for dealing with them. Instead of freezing all operations destined to Chicago at the gates and on the ramps, the gate hold was removed and aircraft were held at the ramps where aircraft are staged for departure. In this example, the pushback delays were eliminated and the time before liftoff was shifted from time at the gate to time on the ramp without causing delays for the departures of other airlines. There was sufficient capacity on the ramp to support continuing operations.

Table4– Weather Scenario with Ramp Hold and no Gate Hold

		Delay (minutes)		Flights with Pushback Delay		Ramp and Taxi time
		Daily Flights	Av. Delay	Number	P(>20 min.)	Av. Minutes
airline	event					
American	2: Arrival	30	7.2	0	0.000	7.2
	4: Departure	36	0.5	0	0.000	16.2
Delta	2: Arrival	18	7.0	0	0.000	7.0
	4: Departure	19	0.0	0	0.000	7.5
United	2: Arrival	25	7.0	0	0.000	7.0
	4: Departure	33	0.2	0	0.000	21.1
US Air	2: Arrival	15	6.8	0	0.000	6.8
	4: Departure	16	0.0	0	0.000	7.6
Southwest	2: Arrival	79	7.6	0	0.000	7.6
	4: Departure	79	0.0	0	0.000	9.1
Overall		350	3.5	0	0.000	9.9

The impact of changes in a sequencing strategy is, however, dependent on the ability of the physical system to accommodate its implementation. The results of the simulated scenarios in Table 3 and Table 4 occurred with capacity of six aircraft at a staging point for departures at the active runway. If the ramp capacity were restricted to four aircraft, there would be less flexibility for maneuvering the aircraft waiting for departure and the effects of removing the gate holds would be magnified downstream. This is illustrated with the results in Table 5 and Table 6.

As seen in Table 4, when the gate hold is imposed, there is sufficient remaining ramp capacity to accommodate other departures without affecting their time on the taxi and ramp. With the reduction in ramp capacity, the effects of removing the gate hold are magnified. This is seen by comparing the statistics in Table 5 with those in Table 3. Pushback delays are eliminated as before, but the delays for departures on the ramp and taxiways are magnified for all carriers – not just for those with departure holds.

These examples were generated using a single replication of scheduled activity of the major airlines for a single day with designated runways for arrivals and departures. To isolate the effects of the operational rules alone, each of the activity times was set at deterministic values (i.e. with variances set to zero).

Table 5 – Weather Scenario with Ramp Hold, Gate Hold and Reduction of Staged Ramp Capacity

		Delay (minutes)		Flights with Pushback Delay		Ramp and Taxi time
		Daily Flights	Av. Delay	Number	P(>20 min.)	Av. Minutes
airline	event					
American	2: Arrival	30	7.2	0	0.000	7.2
	4: Departure	36	8.3	2	0.056	8.8
Delta	2: Arrival	18	7.0	0	0.000	7.0
	4: Departure	19	0.0	0	0.000	7.6
United	2: Arrival	25	7.0	0	0.000	7.0
	4: Departure	33	6.4	2	0.061	15.3
US Air	2: Arrival	15	6.8	0	0.000	6.8
	4: Departure	16	0.0	0	0.000	7.7
Southwest	2: Arrival	79	7.5	0	0.000	7.5
	4: Departure	79	0.6	1	0.013	8.9
Overall		350	5.0	5	0.014	8.6

Table 6 – Weather Scenario with Ramp Hold, No Gate Hold and Reduction of Staged Ramp Capacity

		Delay (minutes)		Flights with Pushback Delay		Ramp and Taxi time
		Daily Flights	Av. Delay	Number	P(>20 min.)	Av. Minutes
airline	event					
American	2: Arrival	30	7.2	0	0.000	7.2
	4: Departure	36	0.5	0	0.000	21.4
Delta	2: Arrival	18	7.1	0	0.000	7.1
	4: Departure	19	0.0	0	0.000	13.6
United	2: Arrival	25	6.9	0	0.000	6.9
	4: Departure	33	0.2	0	0.000	25.3
US Air	2: Arrival	15	6.8	0	0.000	6.8
	4: Departure	16	0.0	0	0.000	10.6
Southwest	2: Arrival	79	7.5	0	0.000	7.5
	4: Departure	79	0.0	0	0.000	14.2
Overall		350	3.5	0	0.000	12.5

To investigate how the effects of different operating conditions and practices would be revealed in practice, multiple replications are required with stochastic times for activities and random generation of interfering events (equipment failure, weather) in accordance with their historical frequencies and durations. One hundred replications of a day's schedule with simple scheduling rules (such as FCFS with priority dispatching from staged queues) requires just a minute of CPU time on a workstation with an Intel® Core™2DuoCPU E8400 processor @ 3.0GHZ and 3.5GB of RAM.

The following tables report the results of simulations with 100 replications of the midweek schedule used above. Random delays are imposed at departure gates using lognormal distributions with means and standard deviations determined from historical data considering time of day and whether the flight is continuing or originating. Other activity times (for taxiing, etc.) were generated using lognormal distributions with a 20% coefficient of variation. The simulation results demonstrate the effects of stochastic variation in departure times upon performance measures. Arrivals were assumed to accrue at the FAF according to schedule (with no random variation).

Table 7 shows the activity and performance for the base case with no adverse weather scenario in Chicago. In parallel with the results for the deterministic simulation, Table 7 shows the simulated performance for an extreme weather event that results in gate holds and ramp holds for flights destined to ORD and MDW from 8AM to noon. Table 8 reflects the results of the same weather scenario without gate holds but imposition of holds on the restricted ramp.

Table 7 – Results of Stochastic Simulation with 100 Replications and No Weather Scenario

Panel A

Key Event		airline					Overall
		American	Delta	United	US Air	Southwest	
1: Touchdown	Number	3,000	1,800	2,500	1,500	7,900	16,700
	Pct	18.0	10.8	15.0	9.0	47.3	100.0
2: Arrival	Number	3,000	1,800	2,500	1,500	7,900	16,700
	Pct	18.0	10.8	15.0	9.0	47.3	100.0
3: Originate	Number	3,600	1,500	2,300	1,600	1,900	10,900
	Pct	33.0	13.8	21.1	14.7	17.4	100.0
4: Pushback	Number	3,598	1,900	3,297	1,600	7,900	18,295
	Pct	19.7	10.4	18.0	8.7	43.2	100.0
5: Liftoff	Number	3,597	1,900	3,297	1,600	7,899	18,293
	Pct	19.7	10.4	18.0	8.7	43.2	100.0
Total	Number	16,795	8,900	13,894	7,800	33,499	80,888
	Pct	20.8	11.0	17.2	9.6	41.4	100.0

Panel B

		Delay (minutes)		Flights with Pushback Delay		Ramp and Taxi time
		Flights	Av. Delay	Number	P(>20 min.)	Av. Minutes
airline	event					
American	2: Arrival	3,000	7.1	0	0.000	7.1
	4: Departure	3,598	9.4	377	0.105	7.7
Delta	2: Arrival	1,800	7.0	0	0.000	7.0
	4: Departure	1,900	5.8	96	0.051	7.7
United	2: Arrival	2,500	7.1	1	0.000	7.1
	4: Departure	3,297	14.9	603	0.183	7.7
US Air	2: Arrival	1,500	7.0	0	0.000	7.0
	4: Departure	1,600	6.2	86	0.054	7.6
Southwest	2: Arrival	7,900	7.5	0	0.000	7.5
	4: Departure	7,900	8.9	776	0.098	8.0
Overall		34,995	8.4	2E3	0.055	7.6

In the later case, aircraft were pushed back when ready for departure but they were held at the staged queuing area on the ramp until the holds on flights to Chicago were lifted. It appears here that 100 replications are sufficient to reveal systematic effects of a significant magnitude. The introduction of random weather events instead of a specifically scheduled scenario may, however, increase the required sample size significantly. So also might the aspect of system performance being studied.

Table 8 – Stochastic Simulation with Severe Weather Scenario at Major Destination Hub and Holds at Gate and Ramp

		Delay (minutes)		Flights with Pushback Delay		Ramp and Taxi time
		Flights	Av. Delay	Number	P(>20 min.)	Av. Minutes
airline	event					
American	2: Arrival	3,000	7.1	0	0.000	7.1
	4: Departure	3,598	17.1	551	0.153	8.1
Delta	2: Arrival	1,800	7.0	0	0.000	7.0
	4: Departure	1,900	5.8	104	0.055	7.7
United	2: Arrival	2,500	7.4	22	0.009	7.4
	4: Departure	3,297	27.4	888	0.269	8.4
US Air	2: Arrival	1,500	7.0	0	0.000	7.0
	4: Departure	1,600	6.7	105	0.066	7.6
Southwest	2: Arrival	7,900	7.5	0	0.000	7.5
	4: Departure	7,899	8.9	859	0.109	8.2
Overall		34,994	10.5	3E3	0.072	7.7

Table 9 – Results of Stochastic Simulation with 100 Replications for Severe Weather Event with No Gate Hold but Ramp Hold with Restricted Ramp Capacity

		Delay (minutes)		Flights with Pushback Delay		Ramp and Taxi time
		Flights	Av. Delay	Number	P(>20 min.)	Av. Minutes
airline	event					
American	2: Arrival	3,000	7.1	0	0.000	7.1
	4: Departure	3,599	9.4	389	0.108	20.7
Delta	2: Arrival	1,800	7.1	0	0.000	7.1
	4: Departure	1,900	5.7	96	0.051	13.3
United	2: Arrival	2,500	7.0	0	0.000	7.0
	4: Departure	3,297	14.7	584	0.177	24.0
US Air	2: Arrival	1,500	7.0	0	0.000	7.0
	4: Departure	1,600	5.9	79	0.049	10.6
Southwest	2: Arrival	7,900	7.5	0	0.000	7.5
	4: Departure	7,894	8.8	766	0.097	13.0
Overall		34,990	8.4	2E3	0.055	12.0

6. Data Required for Model Calibration

Calibration and validation of the model are done with historical data of gate activity maintained by the airport in a data warehouse and with an extract from historical records of detailed flight paths for all aircraft that operated under instrument flight rules (IFR) in the past year. The airport gate data provide, for each flight:

- Arrival or departure indicator
- Scheduled time (of arrival or pushback)
- Actual time (of arrival or pushback)
- Airline indicator
- Flight number
- City (of origin or destination)
- Aircraft tail number
- Time of first bag handled
- Time of last bag handled.

The extract of flight data provide, for each arriving flight:

- Airline indicator
- Flight number
- Aircraft type
- FAF used (and runway)
- Time over FAF
- Touchdown time.

Complementary flight data for departures required for model calibration and validation our level of analysis are:

- Airline indicator
- Flight number
- Aircraft type
- Runway used
- Liftoff time.

With these data, we are able to determine the itineraries of flights that arrive at the airport with continuing legs and generate the files used to activate arrivals and originating flights in the simulation model.

Aviation is particularly prone to the effects of severe weather and airport operations can be affected by conditions or events outside the immediate vicinity. Historical data of weather reports at the airport, at connected hubs and at airports in adjacent ATC sectors through which flights occur allow us to determine the conditions under which the operations took place. Airports at the point of origin for inbound flights and airports at the destination of outbound flights can be grouped according to air traffic control (ATC) sectors. Flows inbound from a sector or hub airport may be adjusted to simulate the effects of unusual conditions or events. Flows outbound from the airport may be similarly regulated.

7. Achieving Proper Analytical Balance

Our simulation prototype was created to facilitate the analysis of airport ground operations with due consideration of the major intersecting spheres of activity and responsibility. It captures essential characteristics of the system in each sphere and links them with staged queues at the interfaces. Optimizing heuristics may be embedded in portions of the Arena simulation model and the effects of their solutions may be tested with consideration of stochastic system behavior. This moves beyond triangulation of analytical methods to the integration of different modeling paradigms. Solutions from deterministic optimizing models may also be driven through the model to see their effects on other aspects of the operation and to examine whether promised gains from their use are achievable in a stochastic environment.

The impact of improved decision-making processes is often highly dependent on the specific problem domain and on the conditions under which the system is operating. In our case, traffic levels have dropped since Lambert was a major hub to TWA and American Airlines; so the impact of innovative scheduling methods will have to be assessed by concentrating on (1) airline schedules at peak travel times, (2) artificially inflating traffic to the higher historical levels, or (3) while the system is under stress from factors such as severe weather.

Traffic flows in the model will need to be refined to investigate detailed changes to specific ramp areas or taxiways. Presently, the model exercises control of flows just by signaling when a runway or taxiway is occupied (as a resource) by another aircraft. Our focus is on conditions at the ends of transportation "routes" that compose taxiways and runways. Once an aircraft "seizes" a resource, the resource element becomes unavailable to others. We recognize the much greater granularity with which engineering models represent the behavior of aircraft in the system. Ours is a two-dimensional view that ignores considerable detail. Additional detail may be incorporated, however, when required to address a specific problem.

A natural use of the model is to analyze the gates, personnel, equipment and dispatching strategies employed for push-backs. Additional gates offer flexibility but come with costs. By linking the gate activity to staging points for arrivals and departures, we consider the interactions that may occur as other airlines in the vicinity similarly manage their affairs.

8. Discussion and Conclusion

Frequently the challenge of creating tools for intelligent decision support for logistics and transportation is to refine analytical models so that they represent necessary details of the operating environment realistically – thus avoiding the "flaw of averages" and assuring their relevance. For strategic planning in the airport environment, we ironically find ourselves striving for balance between highly sophisticated simulation models that represent physical phenomena in microscopic detail on one hand, and analytical models which address broader strategic issues and search for better solutions while ignoring important details of how decisions may be implemented on the other hand. We believe that our analytical framework and simulation model with embedded heuristics can help to achieve such a desirable balance.

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