Assignment 8: Capacity and Demand Estimation

Solution
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Problem 1

An airport shown in Figure 1 is to be studied for capacity analysis. The airport has a standard airport surveillance radar (ASR) which tracks aircraft up to 60 nautical miles form the airport site. The radar has a scan rate of 4 seconds. Tables 1 and 2 show the typical ATC separations at the airport under IMC conditions. Assume the minimum separations under VMC conditions are reduced by 10% from those observed under IMC conditions. All five aircraft groups operate at the airport. The airport has the following technical parameters: a) in-trail delivery error of 14 seconds (because there is a radar at the site), b) departure-arrival separation for both VMC and IMC conditions is 2 nautical miles, c) probability of violation is 5%. Arriving aircraft are "vectored" by ATC to the final approach fix located 10 miles from the runway threshold. Arrivals follow in-trail after crossing the final approach fix. The airport aircraft mix, runway occupancy times and approach speeds are shown in Figure 2.

. Show me a few sample calculations for both opening and closing cases.

a) Calculate the arrival-departure saturation capacity diagram (Pareto diagram) under IMC conditions (show all your work). In your diagram, include at least one point to estimate the departure capacity with 100% arrival priority under mixed runway operations. Show me sample calculations of Tij and Bij so that I can judge your analysis.

b) Repeat part (a) for VMC conditions. Assume departure-departure headways are also reduced by 10% in VMC conditions. Comment on the differences observed. Specifically, comment on the number of departure values obtained with 100% arrivals. Show me sample calculations of Tij and Bij so that I can judge your analysis.

Table 1. Minimum arrival-arrival separations under IMC conditions. Values in are nautical miles. Values Shown Do Not Include Buffers.

Minimum Separation Matrix (nm)			Arrivals-Arrivals		
		Trailing Aircraft (Header Columns)			
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	3	3	3	3	3
Large	4	3	3	3	3
B757	5	4	3	3	3
Heavy	6	5	4	3	3
Superheavy	8	8	8	8	8

Table 2. Minimum departure-departure separations under IMC conditions. Values in are seconds.

Departure-Departure Separation Matrix (seconds)					
		Trailing Aircraft (Header Columns)			
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	60	60	60	60	60
Large	90	60	60	60	60
B757	120	120	60	60	60
Heavy	120	120	120	120	90
Superheavy	150	120	120	120	120

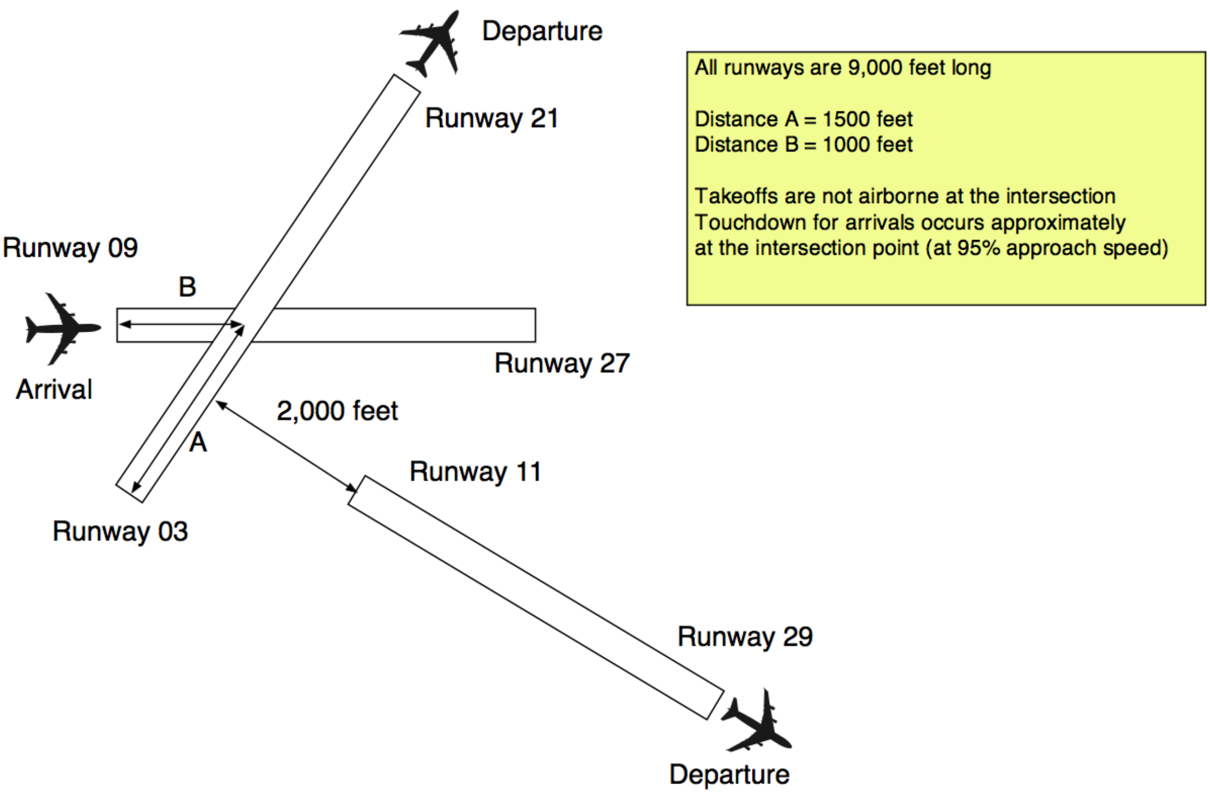

Figure 1. Diagram for Airport of Problem 1.

	Small	Large	B757	Heavy	Superheavy
ROT (s)	48	51	60	65	75
Percent Mix (%)	10	55	10	20	5
Vapproach (knots)	120	140	142	155	150

Figure 2. Airport Arrival Occupancy Times and Fleet Mix for Problem 1.

A few operational rules apply to this airport:

1) Assume a typical acceleration rate on the runway of 2.5 m/s-s for takeoffs.

2) Assume a typical deceleration rate after touchdown of -2.3 m/s-s.

3) All landings on runway 09 occur after the intersection point.

4) Takeoffs on 03 are allowed as long as there is an arrival on 09 that is >=2.0 nm from the threshold 09.

5) Takeoffs on 09R or 14 are allowed as soon as another takeoff has crossed the runway intersection (no wake vortex effect as the aircraft are on the ground).

6) Takeoffs on03 are allowed as soon as an arrival on 09 has crossed the runway intersection (no wake vortex effect as the aircraft are on or very close to the ground). Allow the standard 10 second time lag for ATC to clear the departing aircraft on runway 03.

Break out the problem into two subproblems. The first subproblem is to solve the departures-only capacity for runway 11. The second subproblem solves the capacity of the two-runway intersection set (runways 03 and 09).

Runway 11 analysis can be carried out using the spreadsheet method provided in class. The expected value of the time between successive departures is estimated to be 80.4 seconds. This provides a saturation departure capacity for runway 11 of **44.8 operations per hour**.

$$E(Td_{ij}) = P_{ij} * Td_{ij}$$

where:

Pij = probability that aircraft type i is followed by aircraft type j.

Td_{ij} = is the time between successive departures when an aircraft i is followed by an aircraft of type j.

Pij Matrix					
		Trailing Aircraft (Header Columns)			
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	0.010	0.055	0.010	0.020	0.005
Large	0.055	0.303	0.055	0.110	0.028
B757	0.010	0.055	0.010	0.020	0.005
Heavy	0.020	0.110	0.020	0.040	0.010
Superheavy	0.005	0.028	0.005	0.010	0.003

and the values of Td_{ij} are given below.

Departure-Departure Separation Matrix (seconds)							
		Trailing Aircraft (Header Columns)					
Lead (column 1)	Small	Large	B757	Heavy	Superheavy		Expected Value
Small	60	60	60	60	60		E(Td)
Large	90	60	60	60	60		
B757	120	120	60	60	60		80.4
Heavy	120	120	120	120	90		
Superheavy	150	120	120	120	120		
Departures Only Capacity (per hour)			44.78				

Analysis of runways 03 and 09 requires the following steps:

a) Estimate the arrival saturation capacity of runway 09.

b) Estimate the maximum number of departures possible with 100% arrival priority on runway 03.

c) Estimate the maximum number of departures on runway 03 alone.

The steps outlined above provide 3 data points to construct a Pareto diagram for the runway set 03 and 09.

Step (a) Arrival capacity of runway 09

Expected value of time between successive arrivals with buffer added is 122.2 seconds. This value is E(Tij + Bij). The arrival saturation capacity is 29 operations per hour.

Pij Matrix					
		Trailing Aircraft (Header Columns)			
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	0.010	0.055	0.010	0.020	0.005
Large	0.055	0.303	0.055	0.110	0.028
B757	0.010	0.055	0.010	0.020	0.005
Heavy	0.020	0.110	0.020	0.040	0.010
Superheavy	0.005	0.028	0.005	0.010	0.003

Augmented Matrix (Tij + Bij)							
		Trailing Aircraft (Header Columns)					
Lead (column 1)	Small	Large	B757	Heavy	Superheavy		Expected Value
Small	113.10	100.24	99.16	92.78	95.10		E(Tij) + B(Tij)
Large	168.81	100.24	99.16	92.78	95.10		122.24
B757	196.48	128.13	99.16	92.78	95.10		
Heavy	247.74	164.11	137.27	92.78	95.10		
Superheavy	300.00	232.24	228.62	207.36	215.10		
Arrivals Only Capacity (per hour)			29.00				

$$E(T_{ij} + B_{ij}) = P_{ij} * (T_{ij} + B_{ij})$$

where:

Pij = probability that aircraft type i is followed by aircraft type j.

$T_{ij} + B_{ij}$ = is the time between successive arrivals to runway when an aircraft i is followed by an aircraft of type j. This value only considers the ATC buffer.

Step (b) Departures with 100% arrival priority requires a gap analysis of arrivals on runway 09.

The gap analysis measures the gaps between successive arrivals and compares them with the time needed to release a departure on runway 03. This analysis requires an estimate of the time for arrivals on runway 09 to cross the intersection of runways 09 and 03.

Time to cross intersection		runway 09 arrivals		Distance to intersection		1000	feet
				Conversion feet to nm		0.16462098	
	Small	Large	B757	Heavy	Superheavy'		
Vapproach (knots)	120	140	142	155	150	knots	
Time to cross	4.94	4.23	4.17	3.82	3.95	seconds	

The table above shows that on average, **landing aircraft cross the intersection 4.22 seconds** after crossing threshold 09. Call this time $t_{a-cross} = 4.2 \text{ seconds}$.

At the same time it requires an estimate of the time it takes for departing aircraft in runway 03 to cross the intersection 03-09. Using simple uniform accelerating motion formulas we find that on average it will take 22.1 seconds for a departing aircraft to cross the intersection between runways 03 and 09. Call this time $t_{d-cross} = 22.1 \text{ seconds}$.

The critical time for the release of a departure on runway 03 requires consideration of the two times estimated above. However, we also need to factor two delays times that account for ATC and pilot time lags in the system. The first time is the delay time for the ATC controller to recognize when the landing aircraft has crossed the runway intersection ($t_{ATC-lag} = 10 \text{ seconds}$). This time is usually assumed to be 10 seconds. The second time lag effect is perhaps 10 seconds between ATC clearing an aircraft for takeoff roll and its pilot responding ($t_{pilot-lag} = 10 \text{ seconds}$). Adding all four effects, we realize that arriving aircraft to runway 09 would be 46.3 seconds closer than the time estimates done in the $T_{ij} + B_{ij}$ matrix. The situation is illustrated graphically in Figures 1 and 2.

The gap analysis computations for each arrival gap are shown in Figure 3. These are carried out in a standard spreadsheet format. The calculations start with the arrival-arrival matrix (Tij + Bij). We then subtract the time required to clear one takeoff on runway 03 (calculated above as 46.3 seconds). The new matrix constitutes the critical time left before an arrival crosses the runway threshold of runway 09. These calculation are then converted into distance matrix to estimate how far each arrival is from threshold 09 at the time the departure crosses the intersection point between the two runways (see Figure 2). This calculation is shown in the third table of Figure 3. Finally, we inspect which arrival gaps allow the minimum 2 nm between an arrival and the departure on the intersecting runway (03). This analysis can be automated or carried out manually as shown in Figure 3.

It is important to check if arrival gaps are large enough to allow more than one departure on runway 03. For example, looking at the third matrix presented in Figure 3, we realize that gaps where a Small aircraft trails a Boeing 757, Heavy or Superheavy are large enough to allow 2 or even 3 departures on runway 03. For example, consider the cell Heavy-Small (i.e., a Heavy aircraft is trailed by a Small aircraft). The headway between a departure on runway 03 and the time when the Small aircraft arrives to the runway is estimated to be 201.4 (second matrix in Figure 3). This time translates into 6.41 nm flown at Small aircraft speeds (120 knots). You can verify that such gap allows 2 successive departures on runway 03 on average (verify that for 2 departures 3.7 nm will remain before the Small aircraft reaches the runway threshold 09). Similarly, when a Small aircraft trails a Superheavy, 3 departures are possible on runway 03 in such large gap. Collecting all cells estimated we produce the 4th matrix presented in Figure 3. The matrix shows the number of departures per gap on runway 03 with 100% arrival priority on runway 09.

Finally convert the estimated departures per gaps into Equivalent Departures per Gap (EDij) using the known formula:

$$ED_{ij} = P_{ij} DG_{ij} NG$$

The total number of departures in all gaps is the summation of the previous calculation. The analysis shows 30.4 departures with 100% arrivals.

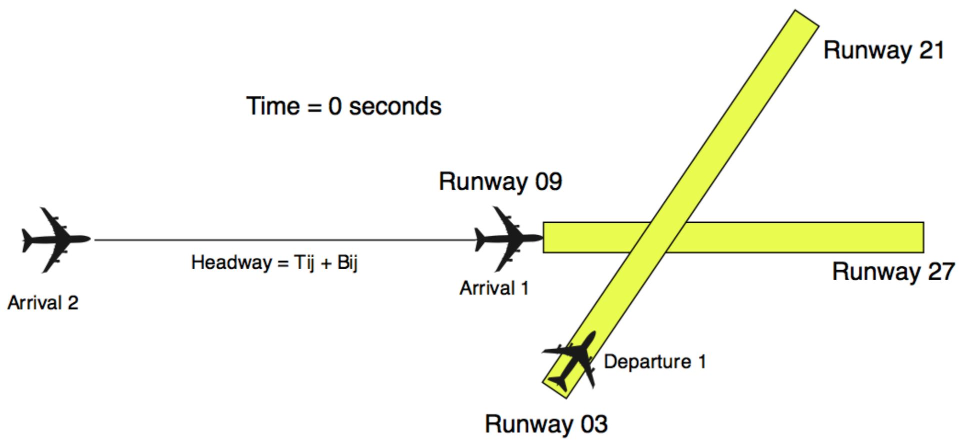

Figure 1. Initial Condition to start Solution for Gap Analysis.

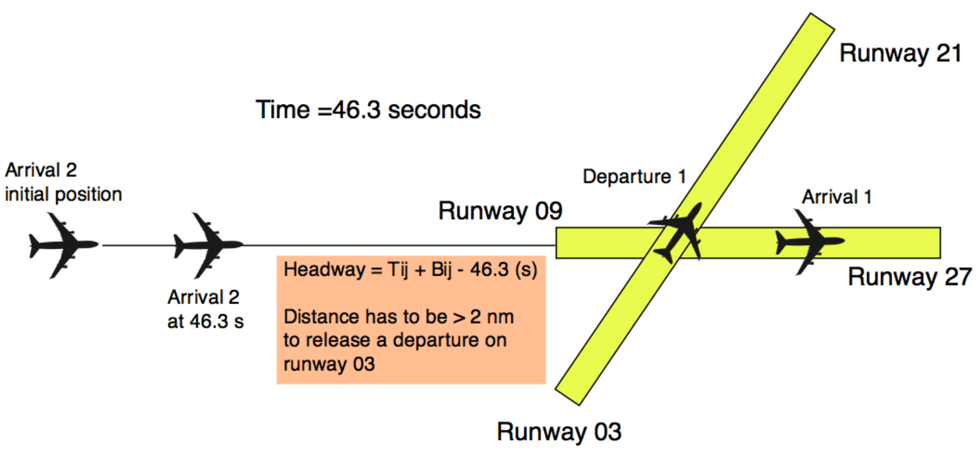

Figure 2. Critical Condition for Release of Departure on Runway 03.

Augmented Matrix (Tij + Bij)					
		Trailing Aircraft (Header Columns)			
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	113.10	100.24	99.16	92.78	95.10
Large	168.81	100.24	99.16	92.78	95.10
B757	196.48	128.13	99.16	92.78	95.10
Heavy	247.74	164.11	137.27	92.78	95.10
Superheavy	300.00	232.24	228.62	207.36	215.10

Tij + Bij - Time for takeoff release (seconds) - One Takeoff on runway 03					
		Trailing Aircraft (Header Columns)			
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	66.79	53.93	52.85	46.47	48.79
Large	122.50	53.93	52.85	46.47	48.79
B757	150.17	81.82	52.85	46.47	48.79
Heavy	201.43	117.80	90.96	46.47	48.79
Superheavy	253.69	185.93	182.31	161.05	168.79

Estimated distance from arrival threshold at takeoff crossing point (nm)					
		Trailing Aircraft (Header Columns)			
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	2.23	2.10	2.08	2.00	2.03
Large	4.08	2.10	2.08	2.00	2.03
B757	5.01	3.18	2.08	2.00	2.03
Heavy	6.71	4.58	3.59	2.00	2.03
Superheavy	8.46	7.23	7.19	6.93	7.03

Number of allowable departures between arrivals per arrival gap					
		Trailing Aircraft (Header Columns)			
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	1	1	1	1	1
Large	1	1	1	1	1
B757	2	1	1	1	1
Heavy	2	1	1	1	1
Superheavy	3	2	2	2	2

Expected departures between arrivals					
		Trailing Aircraft (Header Columns)			
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	0.28	1.54	0.28	0.56	0.14
Large	1.54	8.47	1.54	3.08	0.77
B757	0.56	1.54	0.28	0.56	0.14
Heavy	1.12	3.08	0.56	1.12	0.28
Superheavy	0.42	1.54	0.28	0.56	0.14
Total departures on runway 03		30.4	per hour		

Figure 3. Gap Analysis to Estimate Number of Departures Allowed on Runway 03 for each Arrival Gap on Runway 09.

Using the results obtained before we construct the complete Pareto diagram for the airport with 3 runways. The results are presented in Figure 4. The diagram shows 29 arrivals per hour and a maximum of 89 departures per hour at saturation using both runways 03 and 11 for simultaneous and independent departures (with no arrivals). When 100% priority is given to arrivals on runway 09, runway 03 can service 30.4 departures. Add 44.8 departures on runway 11 and the airport can service 75.2 departures per hour simultaneously besides arrivals. Note that the Pareto (capacity) diagram has a small tradeoff region beyond 75.2 departures because the only way to increase the departure rate is to reduce the number of arrivals on runway 09. The slope of the tradeoff region is steep because the difference between maximum saturation departures and departures with 100% priority is only 15 operations.

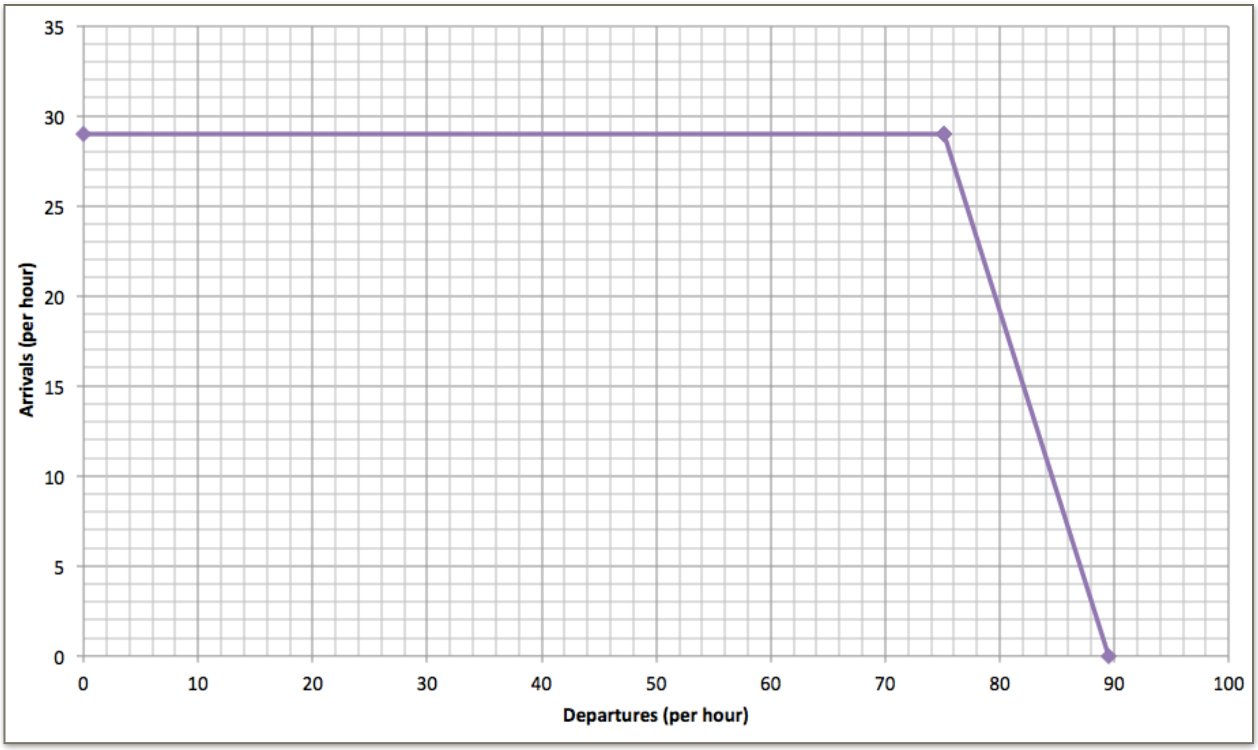

Figure 4. Complete Airport Pareto Diagram.

Problem 2

Familiarize yourself with the passenger data presented below for Cheju International Airport in South Korea. The passenger data has been collected from Wikipedia (http://en.wikipedia.org/wiki/Jeju_International_Airport).

a) The airport has 14 gate positions to service aircraft at the terminal (includes 4 ramp positions). Assume that the ultimate passenger capacity of the existing airport is 29 million passengers per year. Estimate the best parameters of a Logistic forecast demand model for this airport. Use Excel solver in your analysis.
b) Comment on the goodness of fit of the proposed Logistic model.

Table 3. Cheju International Airport Passenger Demand.

Year	Passengers
1997	9,819,129
1998	7,469,980
1999	8,242,134

Year	Passengers
2000	9,125,939
2001	9,320,337
2002	9,939,700
2003	10,802,989
2004	11,104,341
2005	11,354,925
2006	12,109,836
2007	12,296,426
2008	12,448,084
2009	13,643,366
2010	15,724,360
2011	17,201,878
2012	18,443,047
2013	20,055,238

Use Excel Solver to obtain the best coefficients of the logistic regression model.

a=0.1035
b=3.3776
k = 29e6 (given as the capacity of the airport)

Year	Year-1996	Passengers	Logistic Model	Error	Square Error			
1997	1	9,819,129	6,862,624	-2,956,505	8,740,923,690,418			
1998	2	7,469,980	7,419,677	-50,303	2,530,430,710			
1999	3	8,242,134	8,005,595	-236,539	55,950,852,995			
2000	4	9,125,939	8,619,302	-506,637	256,681,503,335	Values of logistic model		
2001	5	9,320,337	9,259,306	-61,031	3,724,812,620			
2002	6	9,939,700	9,923,693	-16,007	256,234,757	a	0.1035311	
2003	7	10,802,989	10,610,129	-192,860	37,194,947,131	b	3.5776591	
2004	8	11,104,341	11,315,882	211,541	44,749,410,106	k	2.90E+07	Capacity
2005	9	11,354,925	12,037,849	682,924	466,385,274,791			
2006	10	12,109,836	12,772,610	662,774	439,269,027,244			
2007	11	12,296,426	13,516,481	1,220,055	1,488,533,656,953			
2008	12	12,448,084	14,265,589	1,817,505	3,303,325,476,797			
2009	13	13,643,366	15,015,952	1,372,586	1,883,991,017,356			
2010	14	15,724,360	15,763,557	39,197	1,536,405,704			
2011	15	17,201,878	16,504,454	-697,424	486,400,325,571			
2012	16	18,443,047	17,234,832	-1,208,215	1,459,783,862,500			
2013	17	20,055,238	17,951,098	-2,104,140	4,427,404,674,217			
2014	18	18,649,945	18,649,945					
2015	19	19,328,405	19,328,405					
2016	20	19,983,891	19,983,891					
2017	21	20,614,226	20,614,226					
2018	22	21,217,654	21,217,654					
2019	23	21,792,842	21,792,842					
2020	24	22,338,865	22,338,865					
2021	25	22,855,184	22,855,184					
2022	26	23,341,619	23,341,619					
2023	27	23,798,312	23,798,312					
2024	28	24,225,683	24,225,683					
2025	29	24,624,398	24,624,398					
2026	30	24,995,319	24,995,319					
2027	31	25,339,472	25,339,472					
2028	32	25,658,003	25,658,003					
2029	33	25,952,150	25,952,150					
2030	34	26,223,210	26,223,210					
				Sum of Squared Error	23,098,641,603,206			

A plot of the resulting logistic regression is shown in Figure 5.

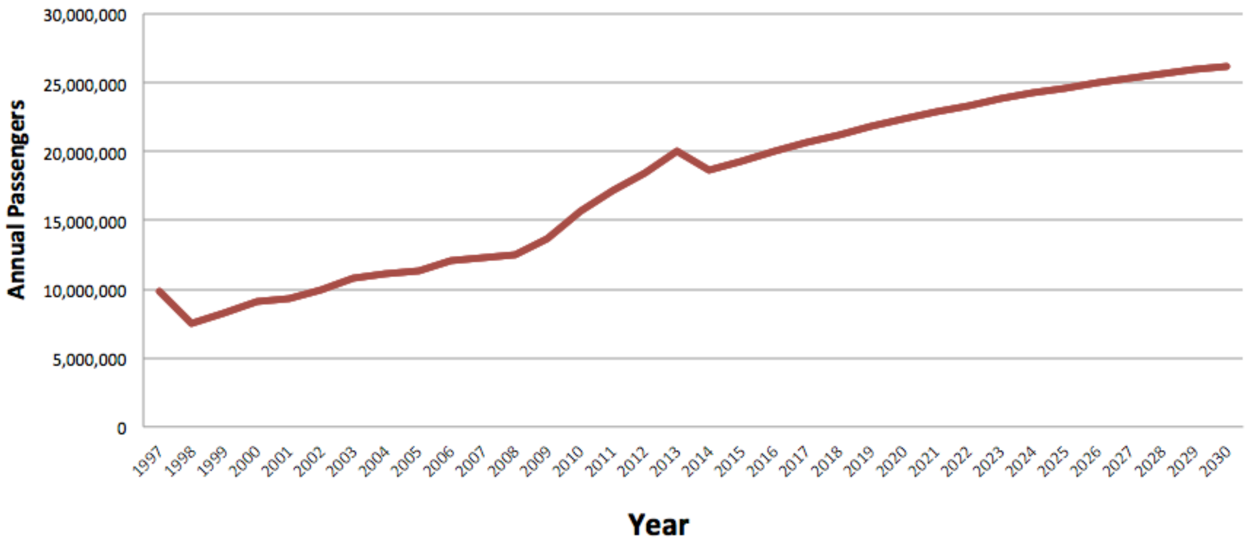

Figure 5. Jeju International Airport Data and Logistic Regression (shown as values after year 2013). Note that the logistic regression is not able to replicate the rapid growth experienced at the airport. For this reason, the solution shows a reduction in annual passengers after between year 2013 and 2014. This is unlikely to happen unless some large shock occurs.

Problem 3

Before building its seventh runway, the Dallas-Forth Worth Airport had a departure saturation capacity of 23 departures per 15-minute period (see red line in Figure 3). The airport is a major hub for American Airlines and back in 2001 had a departure demand as shown in Figure 3. The departure saturation capacity has been estimated using two fully independent runways for departures.

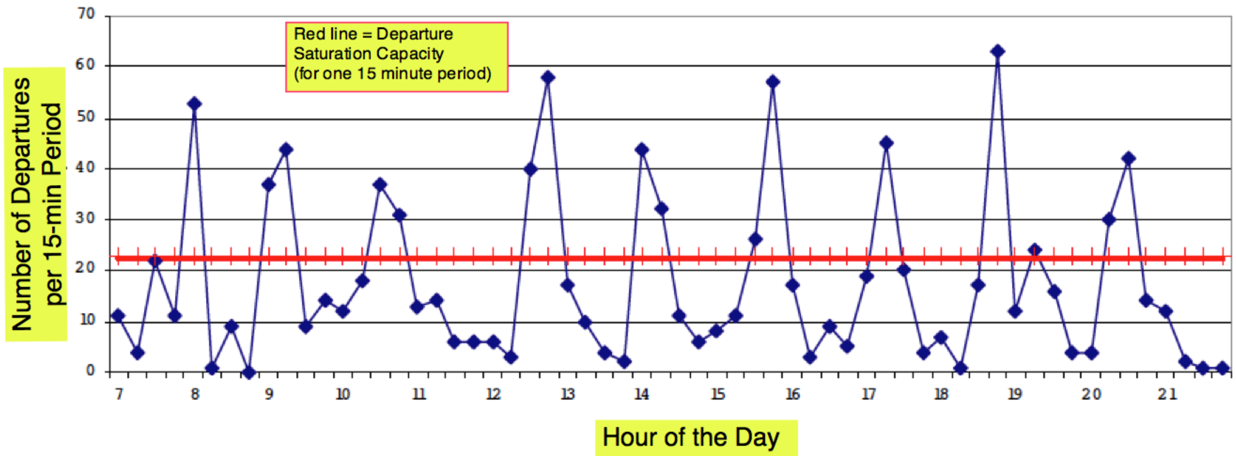

Figure 3. IMC Departure Saturation Capacity (red line) and Scheduled Departure Profile for DFW Airport. Source: FAA Airport Capacity Benchmarks.

a) Convert the graph shown to numerical values of departure demand over time. The conversion is shown below. Note that all demand values are multiplied by 4 because the deterministic queueing model accepts values for capacity and demand rates in aircraft per hour.

```
%        Data for DFW airport

   time      = 7:0.25:21.75;              % values of time (time vector)
   demand = [11 4 22 11 53 1 9 0 37 43 10 14 13 19 38 ...
      31 12 13 5 5 5 3 40 58 18 10 4 2 44 32 11 6 9 11 26 57 ...
      18 3 10 5 19 45 20 3 7 0 18 62 12 24 15 4 4 30 42 13 11 2 1 1 ] * 4;          % values of demand over
noPoints = length(time);

  capacity = ones(1,noPoints) *23 * 4;  % values of capacity over time (baseline capacity of 23 per 15 minute period)
```

b) Estimate the aircraft departure queues that were likely to be experienced before the 7th runway was built.

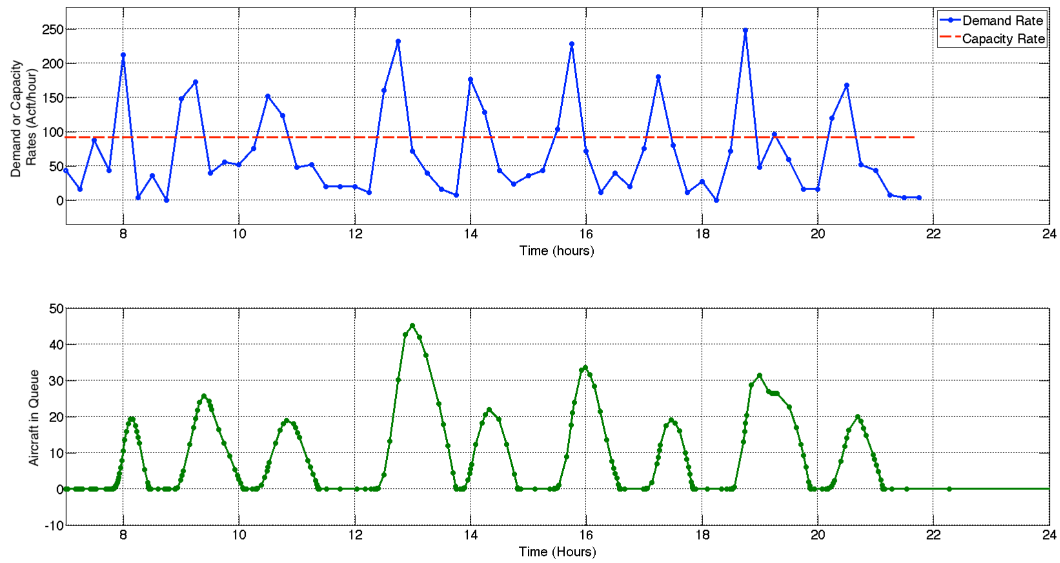

Figure 3.1 Departure Queues Estimated (in Green) Using a Deterministic Queueing Model. DFW without New Runway.

c) Estimate the average delay per departure at DFW using the unsteady queueing model.

The total departure delays based on the deterministic queueing model is estimated to be: 143 aircraft hours. The maximum queue length is 45 aircraft during the period 13:00 hrs as shown in Figure 3.1. The total number of departures at DFW is 1052 aircraft in 24 hours. This translates into an 8.12 minutes of delay per aircraft (counting all aircraft operated in the 24-hour period).

d) Suppose that after adding the 7th runway was constructed, the departure capacity increased by another 35 departures per hour (in IMC conditions). Estimate the new delays at the airport. Assume the demand function remained the same. Was the additional runway justified?

35 departures per hour is equivalent to another 8.75 (35/4) departures in a 15-minute period. Work the problem again with the new parameters. Figure 3.2 shows the new results. Note that the total delay is 38.4 aircraft-hours and the average delay is estimated to be 2.2 minutes. A substantial reduction from the baseline case.

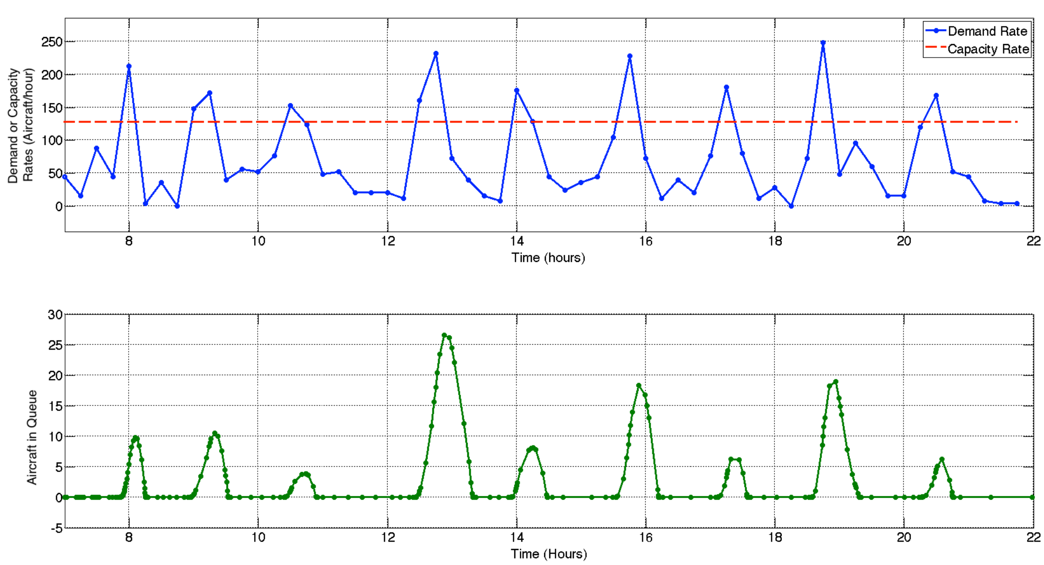

Figure 3.2 Departure Queues Estimated (in Green) Using a Deterministic Queueing Model. DFW with New Runway.

e) Estimate the total delay reductions due to the 7th runway.

The total delay reductions are substantial. From 143 to 38.2 aircraft-hours. The new runway seems to be very useful at reducing departure delays at the airport.