

**Real- options analysis of**  
**Runway expansion at a new airport in Lisbon**



**Abstract**

This paper seeks to value flexibility in the design of a runway system at a new airport in Lisbon in order to recommend whether a flexible design should be used or not. Capacity problems at the current airport in Lisbon, Portela, are expected to occur within the coming years. The Portuguese government therefore decided that a new airport should be constructed in the Lisbon area. This project bears considerable risks. Not only does it entail large initial investments in terms of construction costs, its performance also depends on the highly cyclical and uncertain environment of the aviation industry. The main source of uncertainty affecting profitability of the new airport is passenger demand. The main lever for capacity at an airport is the number of runways. The number of runways therefore is the element of flexibility analyzed in two possible designs (fixed and flexible). In the fixed design two runways are built immediately, whereas only one runway is built immediately in the flexible design with the option to add a second one at a later time. The two designs are analyzed through different methods from real options analysis, two-stage decision analysis and lattice analysis. The flexible design turns out to be considerably more profitable on average in both analyses. A flexible design, that is staged construction of runways, is therefore recommended. The reason for the advantage of the flexible design is based on the value inherent in the flexibility to stay small, and thus to save the cost for unused capacity until it is really needed. The superiority of the flexible design proves robust against different growth scenarios in the lattice analysis. The recommendation for flexible design is therefore given with great confidence.

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## 1. Introduction

This paper explores the use of flexibility in the runway design of a hypothetical new airport in the Lisbon area. Currently there is one airport located in the Lisbon area, Portela, which traditionally serves as a hub for major airlines. It serviced 12 million passengers in 2006 (ANA e Parsons FCG (2006)). This airport, however, cannot be expanded since it is located in a densely populated area. It is projected to reach its capacity constraints in 2009 (Chevalier (2009)). In reaction to pressure since the early 90s, the Portuguese government decided to build a second airport to provide additional capacity in the Portuguese aviation system. (de Neufville (2007))

The maps on the right show the planned location of the New Lisbon Airport (NLA).

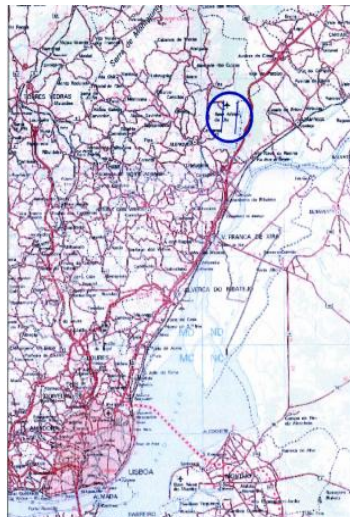


Figure 1: Regional Map  
(ANA SA (2005))



Figure 2: Regional Map  
Duane-Chambers (2007))

Several factors make the design of airports extremely challenging. The construction requires considerable initial investments from the respective governments and potential private-investors. The profitability depends decisively on whether the built capacity is actually used and can generate profit. Traffic development at a new airport, however, depends on variety of sources and is extremely hard to predict. In addition to that is the aviation industry traditionally a highly cyclical one, and an airport has a lifecycle of several decades. All this leads to a situation of high uncertainty for the airport designer (generically assumed as one person), whose decision for the 'right design' is very likely to be suboptimal.

One approach to deal with this uncertainty is to incorporate flexibility in the design. In this paper, the use of real options in runway design is analyzed through different methods of real options analysis to assess its value and give a recommendation about its usefulness in the case of runway design at a new airport in the Lisbon area.

## 2. Description of the runway system and its environment

In this section, the system, its environment, and available data are presented. The first section defines the engineering systems that is the subject of this analysis. The second section gives examples of general sources of uncertainty in air traffic to illustrate the point that air traffic is very difficult to predict and uncertainty needs to be specifically considered in the design of an airport. The third section proposes passenger demand as main source of uncertainty. In the following two sections the demand and cost models and the data to fill these models are presented. The sixth chapter describes the two designs that will be evaluated in this paper.

## 2.1 System description: Capacity side

Capacity is measured in aircraft movements per hour, which includes both departures and landings. Runways very often function as the effective bottleneck of capacity of an airport and are therefore the element in this analysis in which flexibility is included (MIT course 'Airport Systems Planning, Design and Management'(2007)).

The runway system consists of its runways, which are assumed to be parallel and independent. They are assumed to have a maximum capacity of 35 movements/hour. This corresponds to the number expressed in one of the possible construction projects for NLA. (Wikipedia (2007))

The system excludes the gates, terminals, and air bridges and their effect on capacity as runway exit options. Though recognizing their importance as key elements of airport planning, they will be assumed as non-capacity restraining in accordance with most situations found in practice. Separation requirements for aircraft sequencing and the quality and performance of the ATM, while also influencing capacity, are outside of the influential sphere of the runway designer. Their modeling therefore is not of interest in this analysis.

One runway has a capacity of 79, 935 landings per year. Two runways have double the capacity, which is 159,870 landings per year. An equal number of departures and landings is assumed for both runways. The actual capacity in terms of movements (landings and departures) of one runway therefore is 159,870.

The capacity was derived by using the following formula from de Neufville and Odoni (de Neufville, Odoni (2003), p.450-453), which calculates the effective annual capacity from the maximum number of hourly movements of a runway and its yearly standard deviation of demand. The standard deviation of demand of  $\sigma=19\%$  used here is derived from monthly data from 2005 (ANA SA, Bolletim de Estatistica (2005)). In section 4 in this chapter the historical data is presented from which this number was derived.

The formula used to calculate the effective annual capacity is the following:

$$\text{Annual landing capacity} = \text{\#hourly movements} * 16 * 365 * 0.85 * (0.5 + 0.5 / \sigma) * 0.5$$

The number of hourly movements are multiplied by the 16 busiest hours of the day at an airport, by the number of days in the year, by an effective assumed use rate of 85% during these hours, and by a correction for seasonal volatility (higher demand in the summer months).

The system specifically excludes the modeling of capacity reduction due to environmental influences such as inclement weather or delays due to removal of snow or other particles from runway surfaces. The use rate of 85% takes these conditions into account.

## 2.2 Main source of uncertainty: Demand side

*Passenger demand* naturally is the main determinant of the needed capacity for slots at an airport.

*Aircraft mix* is a second determinant of demand for aircraft movements, though at a lesser degree. The change in aircraft types and use rate of these types, the aircraft mix, depends on a number of influences including the airport's competitiveness as a hub, its policy on congestion handling including ground delay programs, and its pricing structure. Within the scope of this paper and for the purpose of focusing on passenger demand as a single uncertainty, however, aircraft mix will be assumed as a constant. Using the same spreadsheet model as in this analysis, the analysis can however easily be modified so that it accounts for the influence of aircraft mix as source of uncertainty.

The uncertainty about the use rate of low cost carriers or legacy airlines of this airport do not play a role in this analysis. Generally, all sorts of customers on the airline side use the same runway, so uncertainty about the *airline customer mix* has a minor effect on the decision about the number of runways (Duane- Chambers (2007), p.67).

## 2.3 General sources of uncertainty in passenger demand

The following listing is intended to give an overview of sources of uncertainty that determine the required and available capacity at an airport. While this list does not make the claim to be exhaustive, the hope is that the examples serve to illustrate the fact that any forecast must necessarily ignore a number of crucial influences that can heavily change the actual development.

*Technical changes*: introduction of new aircraft types (A380, regional jets) with different passenger capacity and separation requirements, introduction of new technology in operations (e.g. RFID in maintenance, repair and overhaul), possibly resulting in quicker operations and turnaround times;

*Economic/ Financial changes*: Internal sources include economic development of the Lisbon area/Portugal with regards to buying power and indogenous passenger demand, and the development of Lisbon as destination for business trips, vacation, conferences, and higher education. External sources include the economic development of Portugal's major trading partners and the development of travel-intensive industries elsewhere which require travel to Lisbon/Portugal. Further economic changes include fuel prices with their effect on airfares and passenger demand;

*Regulatory changes*: regulations of slot allocation processes in Europe and its effect on the attractiveness of a new airport as hub, possible security procedures and effect on demand;

*Industrial changes*: development of competing further airport in the Lisbon area, development of other transportation systems in Portugal like high-speed rail as direct competitors to flights on short-haul routes, expansion of competing airports within a multi-airport system, unclear level of acceptance of the new airport by major legacy and low-cost carriers as hub, or at all, level of future development of low-cost carriers at the new airport whose absence would negatively affect demand;

*Political changes:* future inclusion of the new Eastern European EU members into the tariff and control free Schengen zone which would affect demand from European airports, and possibly role as potential hub;

*Societal changes:* public image of (heavy) air travel in times of rising environmental consciousness, e.g. on short leisure travels, anxiety after plane accidents and possible future terrorist attacks, convenience, space while traveling in alternate vehicles of transportation, such as high-speed trains;

Even though new information mitigates uncertainty, the life span of airports of several decades leaves considerable space for unforeseen developments and events. Sophisticated forecasts therefore need to be viewed as one instance of possible development within a range of other possible developments.

It is assumed in this analysis that passenger demand can be met if airport capacity is sufficient. Airports of course do not only have passengers as customers, but also airlines which have to make a decision to serve a certain airport. In this model we make the assumption that given passengers demanding for flights, there will be aircraft willing to serve them. This is a justifiable assumption given the level of congestion and high demand for slots at other European airports.

## **2.4 Demand and cost model**

Instead of assuming a growth function, this paper uses an existing spreadsheet to model passenger demand (New Airport Runway Model, Duane-Chambers (2007)). This model develops states of passenger demand in each year through the lifecycle, as well as a corresponding probability for each state.

Inputs in this model are initial demand, average annual growth rate, annual standard deviation, and probability for the realization of starting demand. The latter is assumed to be 100%. The expected passenger demand for any period is calculated as the expected demand from the lattice states and corresponding probabilities.

The New Runway Model allows making assumptions for the aircraft mix: aircraft types (in terms of number of seats and weight), landing and parking fees depending on million tons of weight (MTOW), and percentages of use of different types of aircraft.

The following table shows the assumptions for the aircraft mix, which are in accordance with the current situation at several airports (MIT course 'Airport Systems Planning, Design and Management' (2007)).

<b>Aircraft Mix</b>				
	<b>Avg. Capacity</b> [pax]	<b>MTOW</b> [mt]	<b>% Movements</b> [% Total]	<b>Revenue/Landing</b> [\$]
B737-500	115.0	52.6	20.00%	\$342.49
A320-200	162.0	73.9	30.00%	\$342.49
B757-200	190.0	109.3	20.00%	\$342.49
B747-400	382.0	398.3	30.00%	\$533.53
			100.00%	

**Figure 3: Aircraft Mix**

The assumptions for landing and parking fees are based on sample information from Cardiff International Airport, UK, 2007 (cited after Duane-Chambers (2007)).

<b>Revenues Streams by Aircraft Weight</b>			
<b>MTOW min</b> [mt]	<b>MTOW max</b> [mt]	<b>Landing Fees</b> [\$/mt]	<b>Parking Fees</b> [\$/24 hrs]
0	25	31	205
25	200	34	308
200	<i>max</i>	21	513

*mt = metric tonne; parking fees accrued per 24 hrs or part thereof*

**Figure 4: Revenue streams by aircraft weight**

From these assumptions are the following average data derived that facilitate the calculation of revenues.

Average capacity= 224 passengers/aircraft

Average landing fee per aircraft= \$400

Average revenue per passenger= average landing fee/ average capacity=  $\$400/224 = \$1.78$

Annual maximum number of passengers carried

= 35,842,854 (2 runways)

= 17,921,427 (1 runways)

Both airport designs will be compared according to the benefits they generate. The benefit is the profit created by filling aircraft with passengers and charging parking and landing fees (= "aircraft fees") to airlines. The New Runway Model calculates revenues from passenger demand via an intermediate step, the calculation of required movements. The minimum of required movements or available capacity is then multiplied by the average fee per aircraft.

In equations:

(1) Landings required= Passenger demand/(For every aircraft type: Average number of passengers served\*percent share of movements by this aircraft)

(2) Aircraft revenue per landing= Aircraft MTOW\* Landing fee+ parking fee (1 hour)

(3) Total revenue= min (landings required,airport's annual landing capacity)\*(for every aircraft type: Percentage of movement by aircraft\* aircraft revenue)

The calculation of revenue can be simplified and comes down to this equation:

Revenue= Min (Demand in period, available capacity in period)\*\$1.78,

with \$1.78 being the average revenue per passenger.

The lattices of the intermediate steps are included in the spreadsheet of the New Runway Model for their own interest. In this analysis however, only the lattices for demand and revenue are included for reasons of scope of the report.

Costs are created through annual costs of capital for construction and a payment for the expansion option in the flexible case. The cost of construction for one runway is assumed to be \$150mn and is paid back in equal amounts over the lifecycle of the airport (25 years). This equals capital costs of 6mn per year per runway. In addition to capital costs, yearly operating and maintenance expenses of \$2mn are need to be paid for each runway. These payments are independent of the actual level of operation at either runway. All costs depend only on the number of constructed runways and are constant over the life cycle of the airport.

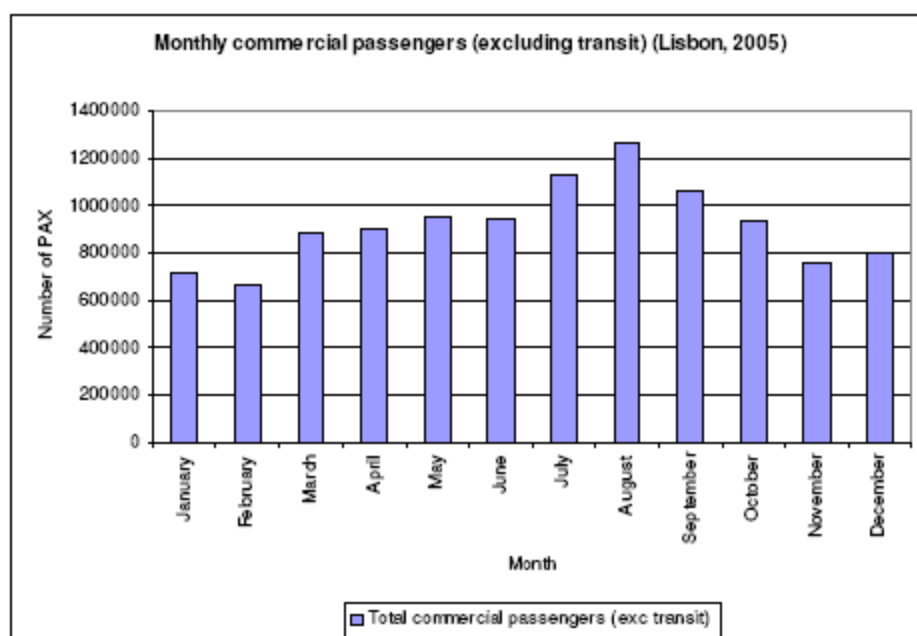
A discount rate of 12 % is employed, which is in line with discount rates used for projects in the private sector.

## 2. 5 Data sources and parameters

Historical data of traffic at the current airport in Lisbon, Portela, is available until 2005 . Traffic estimates for Portela are available until 2016. From 2017- 2050 traffic estimates for some larger time intervals are available for a fictive new airport, that has yet to be built (in the source denoted as 'Ota', but in the following referred to as NLA, as previously). The way the forecast data is presented raises questions about two assumptions. First, the whole traffic shifts to NLA immediately in 2017. This is unlikely. Second, the forecast suggests that Portela does not serve any more traffic as of 2017. This is equally unlikely, since Portela is a working airport with no reason to close. In this analysis it is assumed that NLA serves roughly one third of Portela's projected traffic in 2016 in the year of its opening, 2017, which is 5.5mn, and then develops according to different growth scenarios. (ANA e Parsons FCG (2006), p.14)

From the historical data the yearly standard deviation and the growth rate of the base case are derived. Regression analysis shows that the logarithmic historical data and forecast (1988-2050) follow an exponential growth of the form  $pax(t)=A*\exp(r*t)$ , in which the combined growth rate  $r$  of past data and forecast is 4% ( $R^2=0.95$ ). This growth rate is referred to as base case in the analysis. Of the year 2005 monthly passenger data is available. From this, the variance and standard deviation are calculated. One obtains a standard deviation of 174,094 mn, or 19% in relation to the monthly average of 2005 which is 917, 825.

**Figure 5: Monthly passenger numbers at Portela in 2005**  
(ANA SA, Bolletim de Estatistica (2005))



Month	Total commercial passengers (exc transits)
Jan	716647
Fev	660778
Mar	887994
Abr	898321
Mai	954497
Jun	942255
Jul	1129602
Ago	1265892
Set	1063584
Out	938086
Nov	758239
Dez	798008
Total 2005	11013903

Fonte: ANA SA, Boletim de Estatística 2005

**Figure 6: Passenger forecasts at Portela airport (until 2016) and at NLA (2017- 2050)**  
(ANA e Parsons FCG (2006))

Aeroporto de Lisboa (Portela)

Tráfego Comercial (trânsitos não incluídos)

Valores reais	Ano	Passageiros Anuais (inclui passageiros em transferência)		
	1988	3.995.945		
	1989	4.439.810		
	1990	4.976.194		
	1991	5.056.599		
	1992	5.377.072		
	1993	5.413.490		
	1994	5.755.747		
	1995	6.010.160		
	1996	6.183.009		
	1997	6.631.472		
	1998	7.762.425		
	1999	8.437.350		
	2000	9.213.724		
	2001	9.212.339		
	2002	9.218.131		
	2003	9.502.200		
2004	10.510.228			
2005	11.013.903			
Estimativas	Ano	Passageiros Anuais (inclui passageiros em transferência)	Passageiros em transferência	Passageiros Locais (Chegadas + Partidas)
	2006	11.592.326	2.534.126	9.058.200
	2007	12.279.911	2.621.099	9.658.812
	2008	12.890.982	2.718.841	10.172.140
	2009	13.372.318	2.823.588	10.548.729
	2010	13.870.802	2.938.256	10.932.546
	2011	14.420.543	3.060.315	11.360.228
	2012	15.009.687	3.191.679	11.818.008
	2013	15.637.654	3.332.409	12.305.245
	2014	16.289.922	3.479.482	12.810.441
	2015	16.286.788	3.356.782	12.930.007
2016	16.958.270	3.505.854	13.452.416	

Fonte: ANA e Parsons-FCG

Estimativas	Ano	Passageiros Anuais (inclui passageiros em transferência)	Passageiros em transferência	Passageiros Locais (Chegadas + Partidas)
	2017	17.452.948	3.668.172	13.784.776
	2022	20.931.407	4.895.661	16.035.747
	2030	26.648.816	6.419.114	20.229.702
	2040	34.935.160	8.517.704	26.417.456
	2050	42.108.656	10.304.591	31.804.065

Fonte: Parsons-FCG (Nov. 2006)

## 2.6 Fixed and flexible design

In the *fixed design*, two runways are built immediately. The length of each runway is projected to be 3.6 km, accommodating all types of aircraft including A380. No restrictions apply as to the potential use of runways. The total construction cost of both runways is assumed to be US\$ 300 mn, which are being paid back during an assumed life cycle period of 25 years. The annual operating cost is 4mn for each runway, which accounts for a total annual capital cost of 12mn. Both runways have a total annual capacity of 159,870 landings.

In the *flexible design* only a single runway is built. The decision about a possible second runway can only be made in year 10. The added capacity is available in the period after the extension takes place

(1 and 11). From these points of time on occurs the respective capital cost. Operating cost is 2mn annually for each runway. In the flexible design an option must be purchased in advance to secure the possibility to build a second runway 10 years later, e.g. special preparation of the ground. The cost of the option is US\$ 50mn and will be paid back over 25 years like the capital expenditure for construction. Since the second runway is treated equally as the first runway in terms of payback arrangements, it will not be fully paid back at the end of the lifecycle of the model. A discounted rest cost of \$1.6 mn will not have been paid back in year 25 for the second runway. This heavily discounted rest cost is neglected in this analysis, since it is less than 10% of the relevant results for profits and option values in the following analyses, and, as the reader will see, not a significant influence to the results and recommendations reached.

### 3. Two-stage decision analysis

The following section uses two-stage decision analysis to compare the performance of both design alternatives based on the profits they create.

The New Runway Model, which is used to model demand in this section, is based on a lattice model. It is used as described in the previous section. The development of a demand lattice is illustrated in detail in the following section. For the purpose of the staged decision analysis in this chapter, the demand model could be treated as a black box, which is fed with inputs for initial demand, standard deviation and growth rate of demand, and yields demand and airside value at the end of a period. Airside value is the measure for profit, which is the net expected value of being in a state discounted to the starting year of the lattice.

Even though a lattice model and multiple-stage decision tree are combined here, it should be stressed that this is not a prerequisite for the use of this kind of decision analysis. The growth of demand and profit could be modeled by another forecasting model, e.g. an exponential growth function, instead of a lattice.

The first phase lasts 10 years, until the decision about expansion must be made in the flexible case. The second phase lasts 15 years. One lattice is used for each phase of the decision tree.

The analysis considers three possible annual growth rates for demand. The three growth rates are 2% (pessimistic), 4% (base case) and 10% (optimistic). In step one, the airport planner in each scenario can choose between the two design alternatives, fixed and flexible. After this decision, one of the three growth modes develops during 10 years, yielding the end values for phase 1. In phase 2 one of the growth modes is realized again. The demand is calculated as expected demand from states and probabilities at the end of each lattice, with the expected value for demand in the last period of the first phase being used as initial demand in the second phase. To add up the airside values from both phases and derive a total airside value for each branch of the decision tree, the airside value from phase 2 needs to be discounted over 10 periods. The airside value itself is expressed in terms of the starting period of the lattice.

The following tables serve to illustrate the calculation of the values in the decision tree. They show the calculation of the phase 2 values in the decision tree, given pessimistic development in the first phase and fixed design. The years are based on a hypothetical inauguration of NLA in 2017.

**Figure 7: Phase 1, Fixed design (1 runway + option, 2017- 2027)**

Demand in '17	Average growth rate	Airside value	Demand in '27
5,500,000	2,00%	\$26,660,511	7,708,781
	4,00%	\$21,629,479	9,162,411
	10.00%	\$3,287,268	15,094,207

Airside value is expressed in year 0 -dollars. The expected demand in year 10 (=year 27) is passed on as input to the second calculation. In the following table the airside value of phase 2 is discounted over 10 years („DCF airside value‘). This is added to the airside value of low growth in phase 1, resulting in the discounted value over both periods („DV 2 periods‘). The result is the value of the three growth development paths low-low, low-medium and low-high.

**Figure 8: Values for fixed design (2 runways) in phase 2 (2027- 2042)**

Demand in '27 pessimistic	Average growth rate	Airside value	DCF airside value	Demand in '42	DV 2 periods
7,708,781	2.00%	\$4,826,753	\$1,554,085	13,033,647	\$25,106,426
	4.00%	\$17,663,150	\$5,687,062	17,051,794	\$20,973,449
	10.00%	\$93,035,782	\$29,955,032	37,069,381	\$3,294,521

Values for other growth combinations of fixed and flexible design are derived analogously.

Since no probabilistic estimates for hypothetical growth scenarios („Sc‘) were available, the following assumptions had to be made. The two tables below display the probabilities assumed for different growth modes in phase 1 and 2.

**Figure 9: Probabilities for different growth scenarios**

Phase 1	Pessimistic Sc1, (2%)	Base case Sc 2, (4%)	Optimistic Sc 3,(10%)
1 runway	40%	30%	30%
2 runways	20%	35%	45%

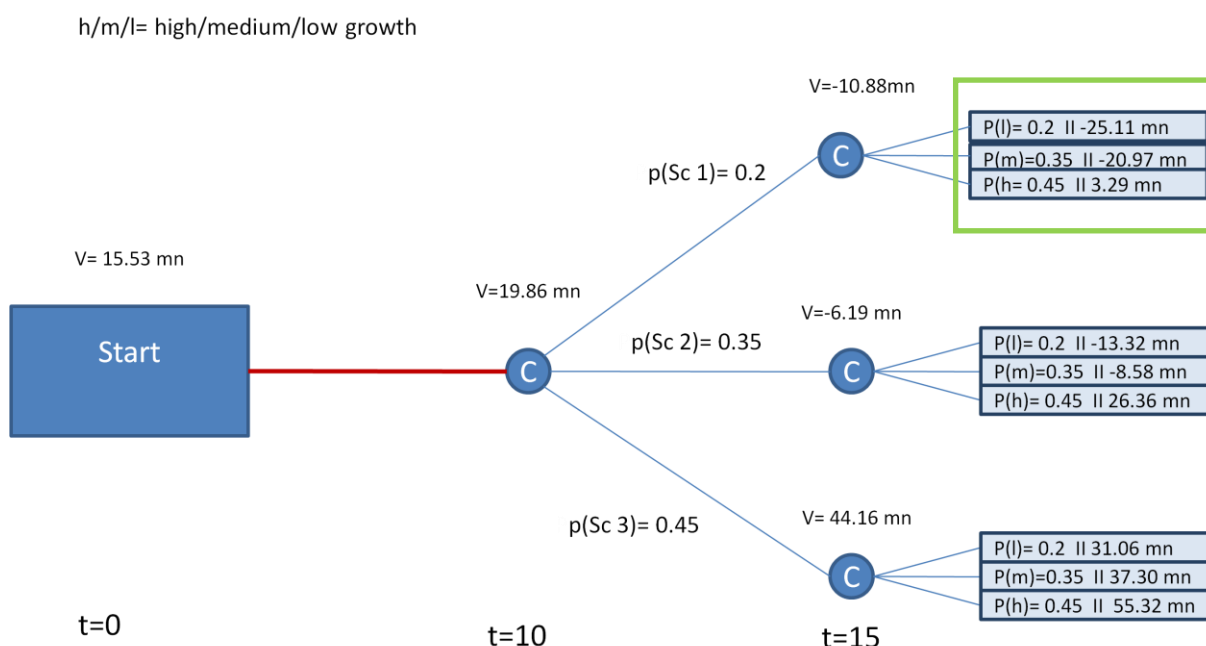
  

Phase 2	Pessimistic Sc 1, (2%)	Base case Sc 2, (4%)	Optimistic Sc 3, (10%)
1 runway	30%	40%	30%
2 runways	20%	35%	45%

The assumptions are meant to incorporate known evidence from several airports that indicate that airlines are attracted to facilities which can accommodate their growth most easily (Bonneyoy (2005)).

These results lead to the following decision tree. Behind each probability are the airside values for step 1 or 2, their beginning marked by the c's for 'chance'. For a better graphical display the two branches for fixed and flexible design are drawn separately.

**Figure 10: Branch for fixed design**



(see following page for Figure 11: Branch for flexible design)

The optimal strategy is to choose the flexible design, and not to expand in the cases of a growth rate of 2% or 4% (pessimistic and base case), and to do expand at a growth rate of 10% in phase 1. The expected value of this strategy is \$ 31.66 mn.

While the expected value in both the fixed and the flexible case is positive (\$15.53mn and \$31.66mn), attention needs to be drawn to the fact that this is naturally very sensitive to the assumptions made for the probabilities of the individual growth paths.

The value increase through the option is \$16.13mn (\$31.66mn- \$15.53 mn=\$16.13m). The initial payment for the option is considered in the calculation of the fixed case.



The values u,d, p were calculated using the following equations:

$$u = \exp(\sigma \cdot \sqrt{\Delta t})$$

$$d = 1/u$$

$$p = 0.5 + 0.5 \cdot \exp((v/\sigma) \cdot \sqrt{\Delta t})$$

The demand lattice (in \$mn) and the probability lattice are shown as shortened versions due to space limits.

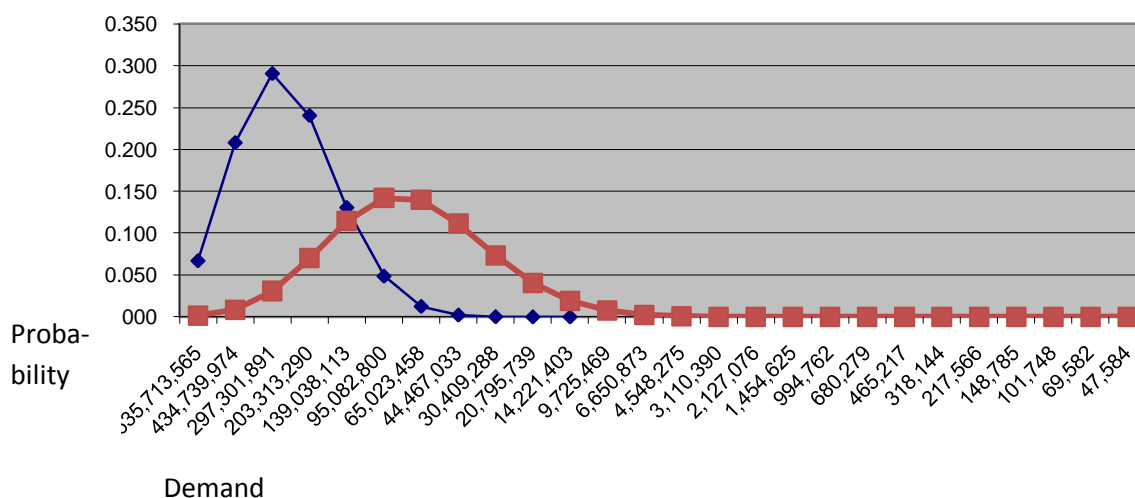
**Figure 13: Demand lattice (in mn)**

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...	21	22	23	24	25
6	7	8	10	12	14	17	21	25	30	37	44	54	65	79		297	360	435	526	636
	5	6	7	8	10	12	14	17	21	25	30	37	44	54		203	246	297	360	435
		4	5	6	7	8	10	12	14	17	21	25	30	37		139	168	203	246	297
			3	4	5	6	7	8	10	12	14	17	21	25		95	115	139	168	203
				3	3	4	5	6	7	8	10	12	14	17		65	79	95	115	139
					2	3	3	4	5	6	7	8	10	12		44	54	65	79	95
						2	2	3	3	4	5	6	7	8		30	37	44	54	65
							1	2	2	3	3	4	5	6		21	25	30	37	44
								1	1	2	2	3	3	4		14	17	21	25	30
									1	1	1	2	2	3		10	12	14	17	21
										1	1	1	1	2		7	8	10	12	14
											1	1	1	1		5	6	7	8	10
												1	1	1		3	4	5	6	7
													1	1		2	3	3	4	5
														1		1	2	2	3	3
															1	1	1	2	2	2
																1	1	1	1	1
																0	1	1	1	1
																	0	0	1	1
																		0	0	0



		0.0	0.0	0.0	0.0
			0.0	0.0	0.0
				0.0	0.0
					0.0

**Figure 15: Probability density function associated with the lattices for period 10 (blue) and 25 (red)**



### 5. Decision analysis using lattice

In this section we use the lattice model to explore flexibility in the runway designs. The intuition behind the method is to compare the current value of having one or two runways in the different states of the lattice in year 10 and base the expansion decision on this comparison. The current value of year 0 given flexibility and the optimal decisions is then compared to the current value in state 0 of the fixed design.

The input parameters for the lattice model are the same as in the previous section.

The lattices of net revenues in the case of having one or two runways serve as the basis for the calculation of current values in individual states. The option cost is subtracted later in the analysis. These feed into the last column of the lattices below. The values in the next column to the left (year 24) are calculated by weighing the two possible states in year 25 by their respective probabilities (0.61 and 0.39 for the base case), discounting the result to the new present (year 24) and adding the respective expected net revenue from year 24.

For reasons of scope the net revenue lattices are not included in this paper. One exemplary calculation of the numbers marked by a triangle shall illustrate how the numbers in the lattices below were derived.

Example:

$$48mn = \min(\text{demand, capacity}) * \text{revenue per passenger} - 2 * (\text{Operating cost} + \text{capital cost}) = \\ \sim 36mn * \$1.78 - 16mn$$

$$91mn = (\text{Prob\_up} * 48mn + \text{Prob\_down} * 48mn) / \text{discount rate} + \text{net revenue from respective state} = \\ 0.61 * 48mn + 0.39 * 48mn / 1.12 + 48mn$$

The following two figures reflect the values of being in a certain state, all expressed in dollars discounted to the respective years. Six years have been omitted for reasons of scope. The current value of year 0, the project value before the start of any construction, is the indicator used for comparing the alternatives.

**Figure 16: Current value of being in a state for 2 runways, 4% growth (in \$ mn)**

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...	21	22	23	24	25
2	17	45	78	114	154	196	241	284	322	348	354	351	343	332		193	163	129	91	48
	31	10	14	42	73	108	147	188	230	271	307	330	334	329		193	163	129	91	48
		50	32	12	11	38	68	102	138	177	218	256	289	309		193	163	129	91	48
			65	51	34	14	8	33	62	94	128	165	202	237		193	163	129	91	48
				78	66	52	35	17	4	28	55	85	116	150		193	163	129	91	48
					88	77	66	52	37	19	1	23	47	74		190	163	129	91	48
						95	87	77	65	52	38	21	3	17		159	154	128	91	48
							101	93	85	75	64	52	38	23		100	108	105	87	48
								105	98	91	83	73	63	51		49	58	62	57	38
									108	102	95	88	79	70		13	23	29	29	21
										109	104	97	91	83		11	2	6	11	9
											109	104	98	92		28	18	9	2	1
												109	104	98		40	30	20	11	4
													107	102		48	38	27	17	8
														105		53	43	32	21	10
																57	47	36	24	12
																59	49	38	26	13
																61	51	40	27	14
																62	52	41	28	15
																63	53	41	29	15

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	63	53	42	29	15
	64	54	42	30	16
		54	43	30	16
			43	30	16
				30	16
					16

**Figure 17: Current value of being in a state for 1 runway, 4% growth (in \$mn)**

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	...	21	22	23	24	25
75	97	120	144	166	183	191	194	193	190	187	183	178	172	166		97	82	64	45	24
	53	73	95	117	140	162	178	186	187	186	182	178	172	166		97	82	64	45	24
		33	51	70	91	114	136	156	172	179	179	176	172	166		97	82	64	45	24
			16	31	48	67	88	109	130	150	164	170	169	165		97	82	64	45	24
				2	14	29	45	63	83	103	124	142	155	159		97	82	64	45	24
					11	0	12	26	42	59	77	96	115	132		97	82	64	45	24
						21	12	1	10	23	38	54	71	88		97	82	64	45	24
							29	21	13	3	8	20	33	48		95	81	64	45	24
								35	29	22	14	5	5	16		86	78	64	45	24
									40	35	29	22	15	6		57	60	57	43	24
										43	39	34	28	22		30	34	35	30	17
											46	42	37	33		10	15	17	16	9
												47	44	40		3	1	5	6	4
													48	45		12	8	4	1	0
														48		19	14	9	5	2
																23	18	13	8	4
																26	21	16	11	5
																28	23	18	12	6
																29	24	19	13	7
																29	25	20	14	7

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										25	23	19	14	7
										25	15	14	12	8
											24	18	12	8
												19	12	8
													12	8
														8

The first lattice gives us the value of the fixed design, which is \$ -2mn. The second lattice calculates the value of having just one runway, which is \$75mn. Both calculations do not include the cost of an option. In order to compare both designs, we need to subtract the option cost in year 10 dollars from the value in year 10, so that the numbers represent the 'full story' of the flexible design.

This was done in the lattice below. The entries for year 10 represent the maximum value of having either 1 or 2 runways, reduced by the present value of the option in year 10, which is 39.5mn (option cost in year 0: 50mn). The annual payments of \$2mn were appropriately discounted to year 10 for all years after year 10, and up-discounted to year 10 for all payments that were due before year 10.

The entries in year 10 represent the value of the optimal choice in year 10. It turns out that this means to expand in the first two, most optimistic cases, and not to in the others. In order to determine the value of the flexible design, we backtrack the current value of different states starting in year 10, as was done before.

**Figure 18: Calculation of present value given the optimal expansion decision in year 10, 4% growth (in \$mn)**

0	1	2	3	4	5	6	7	8	9	10	Ex. Option?
458	550	628	683	709	699	653	580	494	403	308	Yes
	279	364	437	494	526	526	490	419	326	232	Yes
		125	200	266	319	351	354	323	251	139	No
			0	65	123	170	200	205	177	110	No
				-94	-37	15	57	84	89	64	No
					-158	-105	-57	-16	12	20	No
						-193	-141	-92	-49	-16	No
							-201	-146	-93	-43	No
								-184	-123	-61	No
									-144	-74	No
										-83	No

The current value of the flexible case is \$458mn. The value of the option for this and other growth rate is calculated below. The expected net present value (ENPV) of the fixed design is subtracted from the ENPV of the flexible design, when making optimal expansion choices.

**Figure 19: Value of call option to expand depending on growth rates (in \$mn)**

	2%	4%	6%	8%	10%
ENPV (flexible)	313	458	600	731	843
ENPV(fixed)	21	2	21	45	70
Value of call option to expand	334	460	579	686	773

The analysis shows that the option value in base case is \$ 460mn. It should be noted that this is the value the option provides, not an upper boundary for the price of the option, since a price of \$ 50mn is already included in the calculations.

This superiority of the flexible design proves robust against different growth rates in the lattice analysis, as illustrated by the calculations in the table. This indicates that the advantage of flexible design in runway construction in this case mainly lies in the cost saving while traffic demand does not require a second runway, not so much in the value of a flexible reaction to external developments.

## 6. Conclusion

### Recommendation and practical issues

The flexible design turns out to be – on average- considerably more profitable in both analyses. We therefore recommend the staged construction of the runways at NLA. The reason for the advantage of the flexible design is based on the value inherent in the flexibility to stay small, and thus to save the cost for unused capacity until it is needed. The superiority of the flexible design proves robust against different growth scenarios in the lattice analysis. The recommendation for flexible design is therefore given with great confidence (within the assumptions of the model).

This paper was prepared to demonstrate the use of the methods of real options, and used hypothetical data were actual data was not available. The reader should be advised to make careful note of all assumptions and documented sources in this paper.

As a further note needs to be stressed that the evaluation criterion used here was solely profit. In practice, additional criteria will need to be considered by airport operators, such as level of service to airlines. This model, while seeking to use a reasonable capacity level, does not take congestion at the single runway into account that might make a second runway desirable earlier on than from a

financial point of view. Further, a possible positive feedback of available capacity and prime slots on an airline's decision to use NLA as a hub, and hence on growth, is only roughly considered in the decision analysis part, due to lack of information. Insight into the actual situation in Portugal and possibly information from airlines or local airport operators could help refine these assumptions.

The concept of equal annual capital cost used in this model, while unreasonable if interpreted as actual construction costs, can be justified by interpreting them as equal annuities that pay back a loan. In this case, however, the reader needs to be advised that the amount he enters as 'construction costs' of a runway is actually the net present value of his loan and probably a lot higher than the costs of construction.

Lastly, in the decision analysis section a lattice model was treated as a black box forecasting model within the phases of a decision tree. The reader should be advised that the proper way of combining these two models, however, is subject of ongoing research.

### **Note from the author**

This paper was prepared as comprehensive summary of individual assignments in the graduate course 'Engineering Systems Analysis for Design', taught in the fall of 2007 by Prof. Richard de Neufville at Massachusetts Institute for Technology.

The insights I gained during the course and the preparation of the are adressed in this section.

First, option design matters. For a large part of the course I struggled with what turned out to be an unfeasible set-up for the flexible design. The fixed design was a single runway, the flexible design a single runway which came at an unavoidable option cost and the flexibility to build a second runway at additional construction cost. The flexible design was a lot less profitable, in fact, highly deficiatary, and large parts of the analyses to determine the better design seemed superfluous. Possibly the set up of designs with a very unequal distribution of chances and risks is a problem in a class room environment, since in real life the construction of a major new airport with only one runway likely may not have been an option. However, a take-away for future real options analyses surely is that the choice of designs need to be guided by intuition about what designs are comparable in terms of risk and chances (option cost vs. opportunity cost/ unused capacity) or else the analysis would not make sense.

Second, I take away an enhanced appreciation of the effect of discounting and of large time frames, owing to the struggle with different designs and the study of a rather large lifecycle. In both analyses the fixed design was clearly put at a disadvantage since there was no way the costs for the second runway during the first couple years could be recuperated at a later point, since late benefits were heavily discounted.

Generally, while using partially hypothetical data, this analysis supports that the use of flexibility is very valuable in the construction of runways. Reasons are the fact that demand tends to build up gradually, the low economies of scale of runways, and long lifecycle with effects on discounting of future revenues.

I enjoyed taking the course and appreciate the broad and ready applicability of the learned concepts, as well as my improved Excel skills. It was very interesting to see the application of the methods in different concepts both within the course and in portfolios of other students. I am looking forward to the publication of the student portfolios and presentations on the website to gain further insight into the application of real options methods to different domains that students work in.

### **Comments on the New Runway Model**

First of all, in using the model for this analysis, I did not find actual arithmetic mistakes in the formulas. Since part of the goal of using the model was to test its workability, some thoughts about the payback time of the second runway are provided in the following section, since this area in my opinion needs some attention.

The model is constrained to a lifecycle of 25 years. The user enters his choice of lifecycle for the second runway and the construction cost, which will be used to calculate the annual capital cost. Naturally, since the second runway is constructed at a later time than the first runway, the second runway will not be paid back entirely in the scope of the analysis. Depending on when the second runway is constructed, on the discount rate, and its assumed lifecycle, this fact can have a significant influence in that it makes the second runway a lot cheaper than the second one in the fixed design. Encouraging the user to choose a lifecycle such that the (loan for the ) second runway will be fully paid back within the 25 years of the model can be an unreasonable burden if the second runway is constructed at a late point in time, and bears the risk that no reasonable valuation of flexibility can be calculated anymore.

In the , free calculation' spreadsheet in which the optimal point in time for construction of the second runway is determined, the calculation comes down to a tradeoff between deferring cost beyond the horizon of the model and taking advantage of higher revenues. In this paper, this issue was avoided by restricting the exercise of the expansion option to a specific point in time, comparable to a European call option.

An easy improvement is the referencing of input data. The hardcoding of e.g. a lifecycle of 25 years in the calculation currently leads to some confusion with a user who assumes a change in lifecycle would affect the annual capital cost.

A further suggestion for improvement in the model is to subtract the discounted rest cost for the second runway from the airside value in the flexible design. While probably insignificant in many cases due to the heavy discounting, it would prevent unreasonable effects, e.g. when low governmental discount rates are used.

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