A COMPETITIVE AND REAL-OPTIONS FRAMEWORK FOR THE ECONOMIC ANALYSIS OF LARGE AEROSPACE PROGRAMS

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Abstract

Commercial aircraft developments are major endeavors which strain the resources of manufacturers. Financial strains are common, as these programs represent enormous bets for aircraft manufacturers. They are often driven by fixed assumptions when business plans are conceived and by the abundance of uncertainties at both the technical and market levels. Standard methods used for capital budgeting are not well suited to account for uncertainty and fail to capture the dynamic nature of markets and the erosion of market leadership positions over time. The on-going research attempts to overcome some of these challenges by proposing a framework for a dynamic competitive and real-options based methodology that helps optimize aircraft development strategies. The analysis is applied to a commercial aircraft development.

1 Introduction

Airlines are operating in a business environment where uncertainty is ubiquitous, assets are easily transferable and competition is overwhelming [1]. To increase their chance of survival, airlines need to equip themselves with the right assets for their specific operations. At the same time, aircraft and engine development cycles are expensive and the length of research and development forces airframe and engine makers to speculate concerning future airline needs and future states of the world.

Aircraft and engine manufacturers as well as airlines must evaluate aircraft designs in order to assess their economic viability. The first approach is to estimate the development costs, forecast future demand, and assume the future state of the competition. They then estimate the size of the market as well as the market share they aim to capture. Using this information, they decide whether to enter, stay or leave the market.

2 Proposed Methodology

To perform an economic viability analysis, aircraft and engine manufacturers may benefit from a multi-step methodology articulated around four distinct analyses. The first is a product evaluation which the customer undertakes during the fleet planning process. The second is a market dynamics analysis where the different aircraft offerings are compared and market preference shares are estimated. The third is a research and development project valuation which assesses whether or not the aircraft development will be profitable for the manufacturer. Finally, the last step is a competitive analysis which helps down-select the most robust and profitable programs in a competitive environment. The different elements of the economic analysis framework are shown in Fig 1.

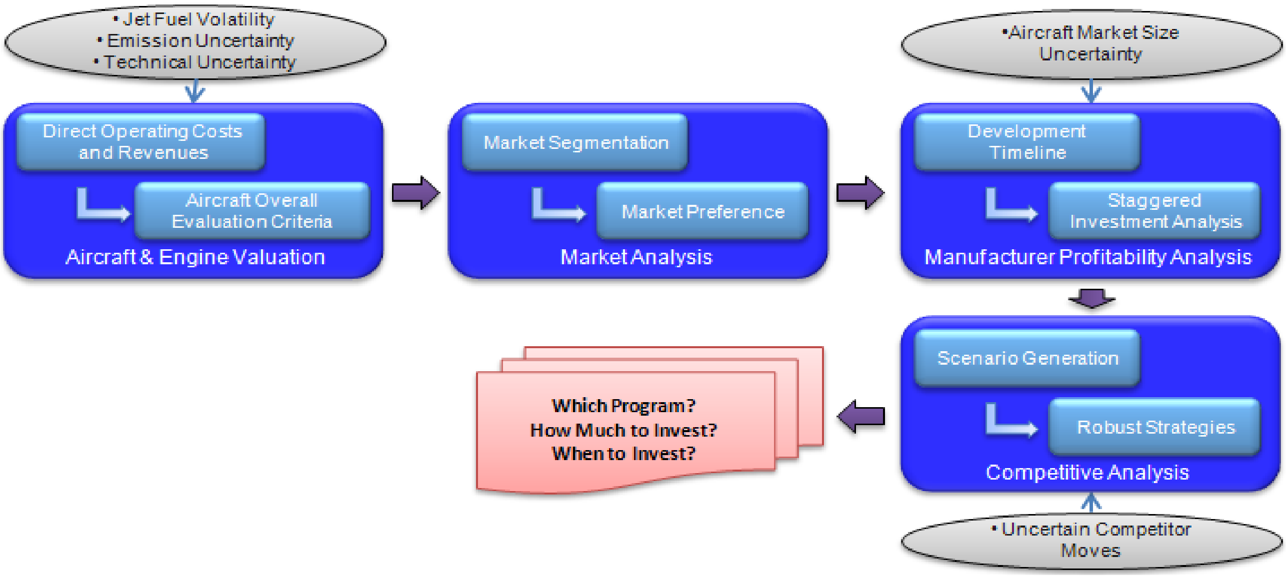


Fig 1: Framework for a commercial aircraft economic analysis

The main contribution of this research is threefold. First, the customer-centric evaluation of aircraft is based on airline schedules and network analyses which permit a reasonably accurate modeling of environmental and operational degradation effects. Then, the profitability analysis is performed using techniques which recognize that management will react to the realization of uncertainty and make rational decisions to improve the bottom line of their company. Finally, a game-theoretic analysis of the competitive environment enables the selection of robust development strategies in the presence of uncertain competitor moves.

2.1 Aircraft Evaluation

The aircraft evaluation is the first step in the methodology. Its purpose is to help understand the behavior of airlines when faced with choices concerning fleet renewal or acquisition process by evaluating the aircraft using the airline point of view. Traditionally, aircraft evaluation for fleet planning purposes is done by assessing aircraft performance over a set of flights that simulate some typical operations and some challenging routes [2]. More recently, surrogate models of costs, revenues and operational performances have been used [3] to both speed up the analysis and allow analysts to undertake a probabilistic aircraft evaluation. Another aspect of aircraft evaluation consists in using a value-based approach where the performance of the aircraft, both from an operational and an economic point of view, is represented by a single metric [4].

The approach proposed in this paper is a value-based aircraft evaluation assessed over an entire airline network. Two independent metrics are first selected to represent the overall performance of the aircraft: the Total Airplane Related Operating Costs (TAROC) and the Total Airplane Related Operating Revenues (TAROR). The airplane-related operating costs and revenues are metrics that focus only on those costs and revenues that are incurred because of the operation of the aircraft and therefore are a direct translation in dollar units of the operating performance of the plane and its suitability for an airline’s network. These two metrics are then mixed together in a single evaluation criterion that represents the overall Net Present Value (NPV) of the aircraft.

Unlike many studies based on surrogate models of costs and revenues, this analysis is carried out using physics-based models whenever possible. For instance, the analysis is performed over an entire network instead of a single generic route. This yields more transparent outputs and synthesized results that are properly balanced. This also allows more accurate estimations of maintenance expenditures and performance degradation over time due to ageing processes.

2.2 Market Analysis

The second step of the proposed methodology is the market analysis whose aim is to assess the market reaction to new product offerings. The analysis starts by segmenting the whole market into different homogeneous segments of customers with similar preferences and requirements. Each market segment is given a weight which represents the market size and potential.

For each market segment, competing aircraft are evaluated using the net present value of cash-flows generated by the operations of the aircraft. Uncertainties regarding the technical performance of the aircraft and regarding the price of commodities are captured by using probability distributions of the inputs in the cash-flow model. In turn, this yields a distribution of NPV in which each data point represents one possible state of the world. Pairwise comparisons of each point across all competing aircraft indicate which one is most suited for a specific state of the world. Aggregating results leads to an estimate of the market share of each competing aircraft in the market segment.

2.3 Staggered Investment Analysis

The third step in the analysis investigates whether the market preferences derived previously are sufficient to ensure the economic viability of the aircraft development program. One of the objectives of this step is to provide decision support for the fundamental questions of if, when and how much to invest in the program.

Capital budgeting methods traditionally use discounted cash flow analysis to assess the economic performance of investments. This is however not well suited for projects involving significant upfront investments such as commercial aircraft development programs. Indeed, with initial investments in the billions and aircraft deliveries starting several years later and stretched over decades, the discounted cash flow analysis often indicate unprofitable programs. Yet, new aircraft developments are undertaken every year.

Part of the problem lays in the fact that a discounted cash flow analysis is deterministic and therefore does not handle well projects spanning over multiple years, featuring several decision tollgates and riddled with uncertainties. One method to assess project viability under uncertainty uses real-options [5]. Real-options analysis is an emerging field in corporate finance [6] where it is used to substantiate capital budgeting decisions. It is derived from the financial options analysis pioneered with the seminal work of Black, Scholes [7] and Merton [8]. Real-options analysis may be interpreted as an extension of the discounted cash flow analysis in that it uses the concept of time-value of money but goes beyond and recognizes the fact that managers react to changes in the business environment and actively steer projects into profitable directions.

Consequently, the real-options approach accounts for the flexibility offered to management to abandon unprofitable programs. This is particularly well suited for aerospace development programs which usually feature milestones and critical tollgate reviews at which programs may be abandoned. In the case of new aircraft developments, the major stochastic drivers affecting the profitability include the growth of air transportation, the retirement of older less-efficient aircraft as well as the evolution of jet-fuel prices.

2.4 Competitive Analysis

The profitability analysis enables the “pruning” of unprofitable aircraft development options. What is left is a portfolio of profitable options or strategies (aircraft developments and associated timelines). Funding constraints usually preclude the nurturing of each and every strategy in the portfolio and decision-makers must choose a single one.

Many advances have been made in the field of strategic decision-making and innovative approaches and algorithms have been proposed in the field of game theory. Game theory presents a means of approaching problems involving competitors and decision-making using a rational argumentation. A game is a model of a competitive situation, and game theory is a set of mathematical methods for analyzing these models and selecting optimal strategies. Even without complete knowledge of an opponent's decisions or resources, game theory is useful for enumerating the decisions available, and evaluating these options, or "moves". When a company's investment decisions are contingent upon the competitor's moves, it becomes a helpful tool in evaluating strategic decisions because it includes a means of predicting how competitors will behave.

Two pioneers [9] in this field assert that "following the rules of game theory can help reduce a complex strategic problem into a simple analytical structure consisting of four dimensions" which include the players, the actions available to them, the timing of these actions and the payoff structure of each possible outcome.

The most commonly used solutions are equilibrium concepts, of which the Nash equilibrium is the most famous. "The Nash equilibrium is a profile of strategies such that each player's strategy is an optimal response to the other players' strategies" [10]. In other words, the quest for a Nash equilibrium is an optimization process performed in the action space which search for a set of actions and reactions from which none of the competitor has any incentive to deviate.

3 Scenario Under Investigation

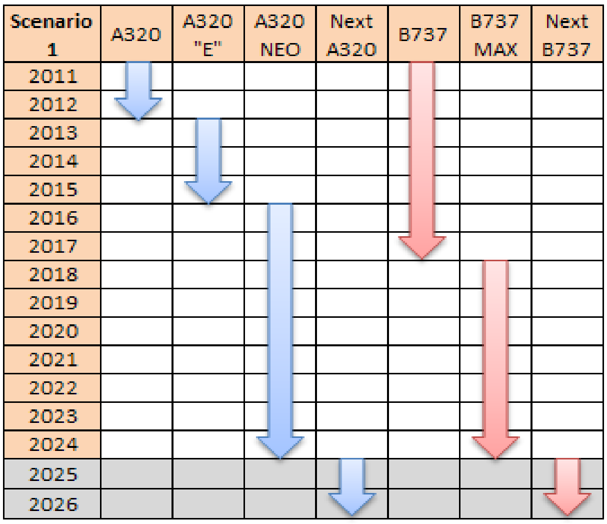
In early 2006, Bombardier announced it would launch the CSeries aircraft family using a new fuel-efficient propulsion system centered on the PW1500G geared turbofan engine offered by Pratt & Whitney.

This increased the competitive pressure at the lower end of Airbus' product line and eventually led the manufacturer to evaluate possible improvements to its current A320 family. In late 2010, Airbus launched two new programs. One is a low-risk enhancement to the current A320 dubbed A320E and featuring a new interior design and new wing-tip devices. The other one, dubbed the New Engine Option (NEO) is longer-term and is articulated around the Pratt & Whitney PW1100G geared turbofan.

On the other side, Boeing is in a more complicated situation where the MAX re-engine of the 737 aircraft is costly due to the low ground clearance of the current 737 and a clean-sheet design might not yield enough improvements to justify the massive investment. Five scenarios inspired by the current state of the business are constructed to test the methodology. These are described in Table 1.

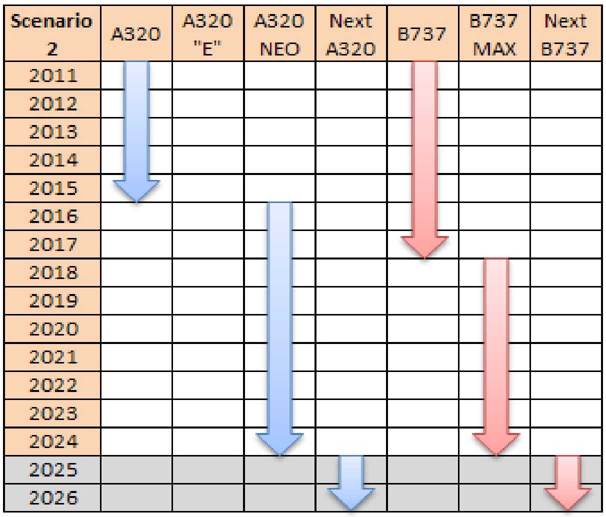
Table 1: Description of scenarios

- Scenario 1: Airbus delivers the first enhanced A320E in 2013, the first re-engined A320NEO in 2016 and a new clean-sheet design in 2025. Boeing delivers the first re-engined 737MAX in 2018 and a new clean-sheet design in 2025



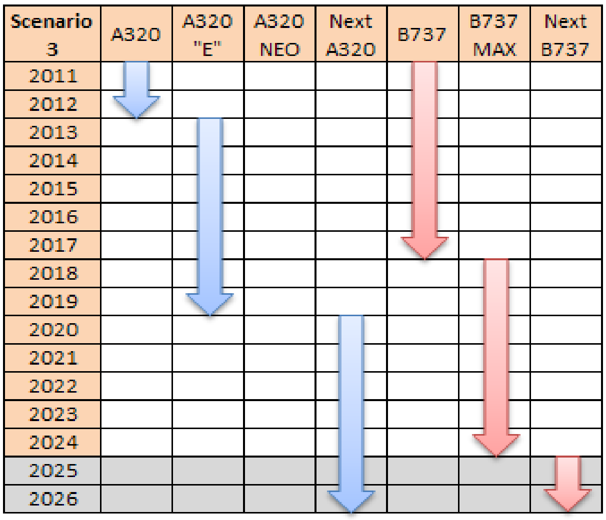
Scenario 1	A320	A320 "E"	A320 NEO	Next A320	B737	B737 MAX	Next B737
2011	↓				↓		
2012	↓				↓		
2013		↓			↓		
2014		↓			↓		
2015		↓			↓		
2016			↓		↓		
2017			↓		↓		
2018			↓			↓	
2019			↓			↓	
2020			↓			↓	
2021			↓			↓	
2022			↓			↓	
2023			↓			↓	
2024			↓			↓	
2025				↓			↓
2026				↓			↓

- Scenario 2: Airbus skips the enhanced A320E development and delivers the first re-engined A320NEO in 2016 as well as the first clean-sheet A320 replacement in 2025. Boeing delivers the first re-engined 737MAX in 2018 and a new clean-sheet 737 replacement in 2025.

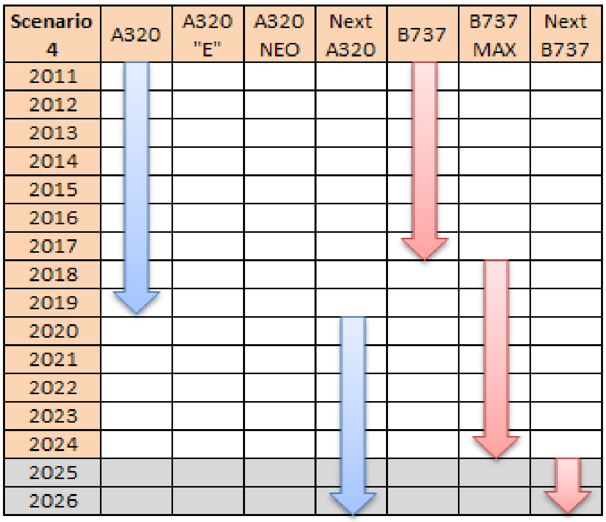


Scenario 2	A320	A320 "E"	A320 NEO	Next A320	B737	B737 MAX	Next B737
2011	↓				↓		
2012	↓				↓		
2013	↓				↓		
2014	↓				↓		
2015	↓				↓		
2016			↓		↓		
2017			↓		↓		
2018			↓			↓	
2019			↓			↓	
2020			↓			↓	
2021			↓			↓	
2022			↓			↓	
2023			↓			↓	
2024			↓			↓	
2025				↓			↓
2026				↓			↓

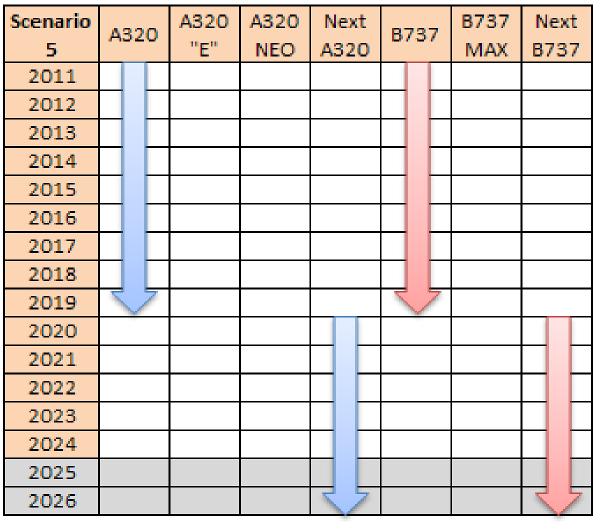
- Scenario 3: Airbus delivers the A320E in 2013, skips the A320NEO to bring the new A320 in 2020. Boeing delivers the 737MAX in 2018 and a new 737 in 2025.



- Scenario 4: Airbus skips both the A320E and the A320NEO to bring the new A320 in 2020. Boeing delivers the 737MAX in 2018 and a new 737 in 2025.



- Scenario 5: Airbus and Boeing skip the intermediate versions to deliver the new A320 and 737 in 2020.



4 Uncertainty Quantification and Modeling

The development of complex aerospace systems-of-systems and the extensive certification processes lead to long development timelines which exacerbate the effects of uncertainty. Uncertainty might be split into two categories. One category is for technical uncertainty over which manufacturers have some control (such as performance estimates). Manufacturers may limit the adverse effects of technical uncertainty by implementing mature technologies in their designs or by using conservative estimates.

The other category is for market uncertainty which manufacturer do not control (such as commodity prices). Owing to this lack of control, aircraft manufacturers must come up with solutions to hedge against these uncertainties to ensure that their decision-making process is optimal and robust regardless of the evolution of the uncertain parameters. Numerous market uncertainties affect manufacturers but only a few have profound effects on the viability of aircraft development programs. One of them is the price of jet fuel which drives the need for new more efficient aircraft to replace older ones since fuel expenditures account for a large part of aircraft operating costs. Consequently, increasing fuel prices affects the profitability of airlines and puts pressure on airlines to renew their fleets.

Another uncertainty which may have some impact in the future is the taxation of carbon dioxide emissions. Little information regarding the effects of such regulations on aircraft manufacturers is available due to the newness of the taxation scheme. Indeed, the European Union has recently set-up the Emissions Trading Scheme whereby airlines must buy permits for roughly fifteen percent of their carbon dioxide emissions starting in 2013.

4.1 Uncertain Technology Effects

Over the course of the A320 and B737 re-engine, several new technologies will be infused in the current design. These include new lightweight cabin interiors, new winglets, new geared turbofans, and new Aluminum-Lithium alloys. In addition, for the A320 and B737 replacement, it is assumed that variable camber wings, active load alleviation systems and composite primary structures will be used. Each of these technologies carries some uncertainty regarding its impact on the aircraft empty weight and induced drag as shown in Table 2. The uncertainty is modeled using probabilistic triangular distributions.

Table 2: Technology impact matrix [11]

Technology Impact Factors	Geared Turbofan		Winglet		Composite Primary	
	Best	Worst	Best	Worst	Best	Worst
Wing Weight			0.02	0.05	-0.45	-0.1
Fuselage Weight			-0.02	-0.02	-0.3	-0.1
Empenage Weight					-0.1	0
Hydraulic Weight						
Electrical Weight						
Cabin Weight						
APU weight						
CDi			-0.07	-0.04		
CDf						
SFC	-0.12	-0.05				
Engine Weight	-0.05	0				

4.2 Uncertain Jet Fuel Costs

The jet-fuel price analysis is performed using data from the United States Energy Information Administration representing the historical time series of U.S. Gulf Coast kerosene-type jet-fuel spot price [12]. The time series is plotted in and looks similar to many financial time series with high volatility and no obvious autocorrelation structure.

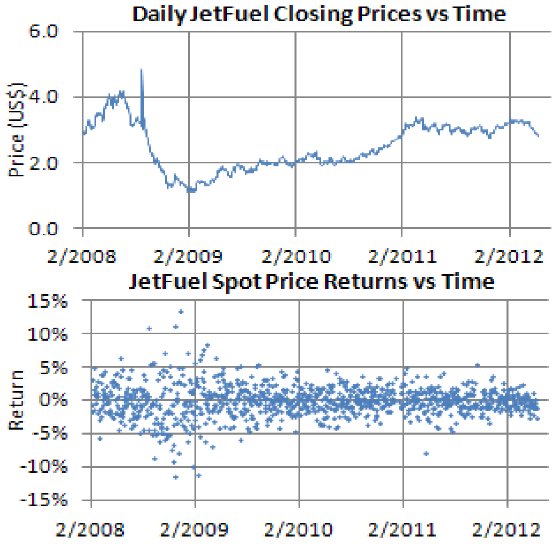


Fig 2 (a) Closing price of jet fuel; (b) Continuously compounded daily jet fuel price returns

Inspection of the continuous returns of the price time series indicates a bell-shaped distribution of the return centered on zero with some clustering of high volatility as shown in Fig 3. Despite this heteroscedasticity, a stochastic model similar to a random walk, the Geometric Brownian Motion (GBM) is hypothesized.

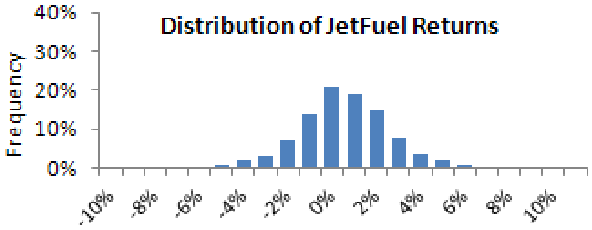


Fig 3: Distribution of daily jet fuel price returns

Several statistical tests are run to check whether this assumption can be rejected at the usual 5% level of significance:

- The first test is the Variance Ratio test as described by Campbell et al.[13]. This test checks the correlation structure of the increments. Under the GBM assumptions, the increments are uncorrelated. The autocorrelation is studied at lags 2, 4, 8 and 16 days, and for each analysis, the test fails to reject the GBM assumption.
- The second test is the Cowles-Jones Ratio test described again in [13] which checks whether the increments are independent and identically distributed. Under the GBM assumption, the increments are independent and identically distributed. This test also fails to reject the GBM assumption which means that the apparent heteroscedasticity previously observed is not significant.

Based on these results, a geometric Brownian motion is used to model the stochastic process driving the price of jet-fuel. The stochastic differential equation is given in (1) with the Wiener process (W_t), the spot price (S_t), yearly drift (μ) and yearly volatility (σ).

$$\begin{gathered} \boldsymbol{dS_t = \mu \cdot S_t \cdot dt + \sigma \cdot S_t \cdot dW_t} \\ \boldsymbol{S_t = 2.75US\$ \,;\, \mu = .005\% \,;\, \sigma = 43.9\%} \end{gathered} \qquad (1)$$

4.3 Uncertain Emission Costs

The Emissions Trading Scheme requires airlines to buy permits for about fifteen percent of the airlines' carbon dioxide emissions. These permits are in limited quantity and may be purchased on the carbon market in the form of European Union Allowances (EUA). For instance, Air France started using the BlueNext exchange platform in 2012 to buy EUAs on the spot market [14].

The carbon emission analysis is therefore performed using the BNS EUA 08-12 time-series available on the exchange website for data from February 2008 to June 2012 [15]. Like the previous example, the time-series plotted in Fig 4 exhibits high volatility, with no obvious autocorrelation structure but with a downward trend.

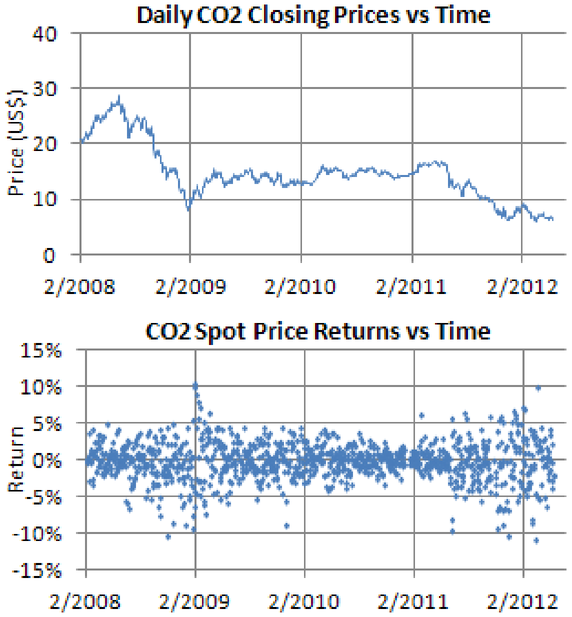


Fig 4 (a) Closing price of EUA; (b) Continuously compounded daily EUA price returns

Inspection of the continuous returns distribution displayed in Fig 5 indicates a bell-shaped distribution of the returns centered around zero with some clustering of high volatility. Based on these observations, a geometric Brownian motion is hypothesized.

The same statistical tests are run to check whether the GBM assumption can be rejected at the 5% level of significance:

- The Variance Ratio test is run for lags 2, 4, 8 and 16 days, and each time the GBM assumption cannot be rejected.
- The Cowles-Jones Ratio test is run and also fails to reject the GBM assumption.

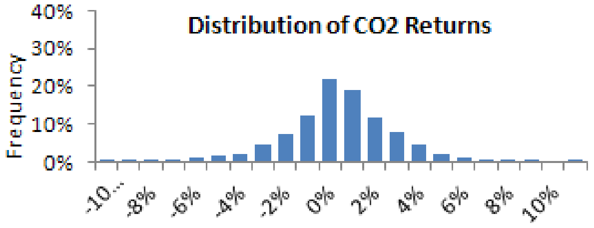


Fig 5: Distribution of daily EUA price returns

Based on these results, a geometric Brownian motion is used to model the stochastic process driving the price of carbon allowances and its parameters are provided in (2).

$$\begin{gathered} dS_t = \mu \cdot S_t \cdot dt + \sigma \cdot S_t \cdot dW_t \\ S_t = 6.26\ US\$\ ;\ \mu = 28.8\%\ ;\ \sigma = 43.5\% \end{gathered} \qquad (2)$$

4.4 Treatment of Correlations

The two stochastic processes retained for the modeling of jet-fuel price and carbon emission cost uncertainty are independent models. However, a more intricate relationship between the two models is likely. Indeed, a period of strong growth in Europe may result in higher demand for air transportation and therefore higher prices for jet-fuel. Similarly, this higher demand for air transportation may result in more demand for carbon permits and therefore higher emission allowance prices.

The relationship between the price of jet-fuel and the price of carbon permits can be captured with the correlation matrix. This matrix is estimated by first cleaning the time series to ensure that quotes are available for both on the same date and then estimating the correlation between the continuous returns of each time series. The correlation matrix is given in (3) and indicates a correlation of 19% between the two data series.

$$M_{Cor} = \begin{bmatrix} 1 & 0.199 \\ 0.199 & 1 \end{bmatrix} \qquad (3)$$

To include this correlation in the two stochastic models previously defined, correlated numbers need to be sampled from the standard normal distribution used in the geometric Brownian motion. This is performed using a Cholesky decomposition of the correlation matrix as shown in (4). The positive definite correlation matrix is decomposed to give a lower-triangular matrix which, when applied to a vector of uncorrelated samples, produces a sample vector with the correlation properties of the system being modeled.

$$\boldsymbol{M_{Cor}} = \boldsymbol{C} \cdot \boldsymbol{C^T} \; ; \; \boldsymbol{C} = \begin{bmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0.199} & \mathbf{0.979} \end{bmatrix} \qquad (4)$$

5 Aircraft Evaluation

The analysis starts with the design of a modeling and simulation environment to analyze the technical and economic performance of commercial aircraft operated on an airline network. The approach aims at mimicking the analysis performed by airlines during sales campaigns and at improving the understanding of airlines behavior when faced with choices regarding their fleet acquisition process.

The evaluation is articulated in three subparts. The first part is a network analysis that uses an airline schedule and network to perform flight performance estimations. The second part is the evaluation of total airplane-related operating revenues based on the payload computations assessed previously. The last part is the analysis of total airplane-related operating costs using again the outputs from the network analysis. Gathering the results allows the estimation of present and future cash-flows that are airline-specific. This analysis has been previously discussed by Justin et al [16].

The airline study looks at the schedule of flights operated by a prospective customer and extracts the flights operated by a subfleet of aircraft to be replaced. The subfleet schedule is processed by a mission analysis software such as the NASA Flight Optimization System performance and sizing code. This yields estimates of the block time, block fuel and payload for each mission.

To differentiate between the products offered, the research tracks the TAROC and TAROR metrics. A description of the factors entering the computation is given in Fig 6.The choice of these two metrics is also motivated by the fact that they are generally accepted by the industry and provide a global picture of the operating performance of the aircraft.

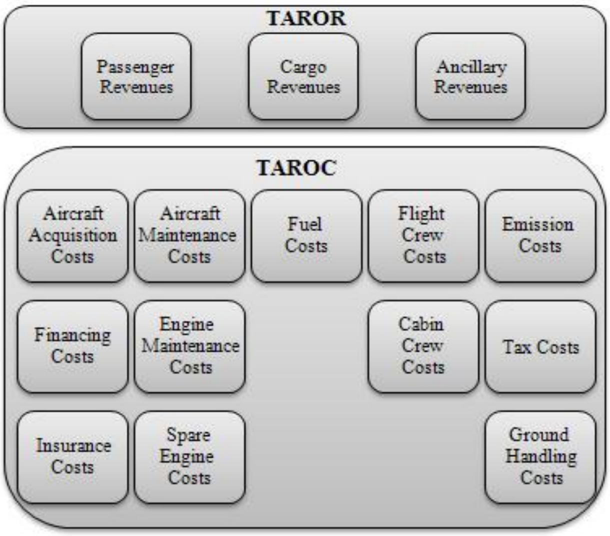


Fig 6 (a) Total airplane related operating revenues; (b) Total airplane related operating costs

Some of the costs are sensitive to the type of operations of the airline. This is the case of engine maintenance costs which vary with the thrust derate used, the environmental conditions (outside temperature, erosive-corrosive property of the ambient air) and the flight length to flight cycle ratio. The treatment of these effects is described by Justin and Mavris [17] and is accounted for using a composite severity factor which modulates the engine maintenance costs according to the harshness of the operations.

Uncertainty abounds regarding some of the inputs used for the revenues and costs estimations. This is for instance the case of fuel burn and carbon emission costs which are not known with certainty for future designs. In this case, a probabilistic approach is undertaken for which inputs are replaced by distributions spanning over the range of most likely values.

The aircraft value is assessed next using TAROR and TAROC. The two metrics yield estimates of the net present value of the aircraft since they represent the cash flows generated by the operations of the aircraft. With the costs subtracted from the revenues and discounted appropriately, an initial estimate of the net present value of the aircraft is computed. This represents how much value is created by operating the aircraft and therefore how customers value the design. Indeed, Gibson [18] reports that the net present value is still the airline managers' preferred and most widely used metric to value investments.

6 Market Analysis

The purpose of the competitive analysis is to assess the market reaction to the offerings of aircraft manufacturers. This is done by first creating different customer profiles representing various types of airlines each with their own set of requirements.

There is however a wide variety of customers as the airline industry encompasses ultra low-cost airlines and legacy airlines, mostly domestic airlines and international airlines. It is assumed that this variety of customers is well captured by using sample airlines networks each with its average flight-hour to flight-cycle ratio and average yearly aircraft utilizations. Each of these representative airlines defines a particular market segment, the size of which is commensurate with the fleet size of the airlines represented.

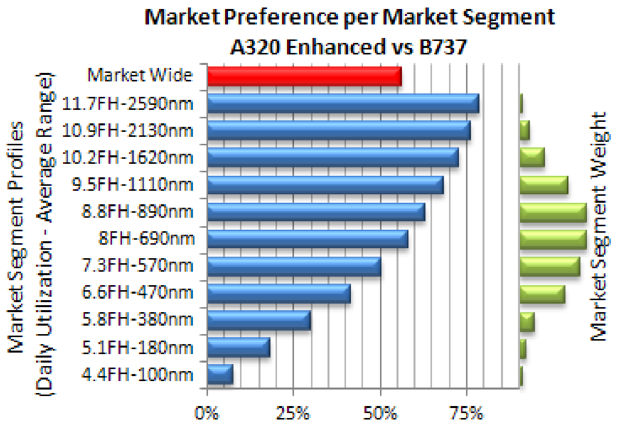


Fig 7: Market preference per segment and segment weight

With different market segments defined, the aircraft evaluation is performed and it yields a distribution of net present values using the aircraft valuation methodology presented before. The net present values are estimated for each segment and for each aircraft in competition within that segment. The aircraft with the highest NPV is the aircraft best suited for the customer's type of operations and is selected as the sale's winner. Results for the competition between the A320E and the baseline B737 are presented in Fig 7.

So far the results are fragmented and market preference estimates are obtained for each market segment. To recombine all these results, the preference of each market segment is multiplied by the segment's share of the entire market to yield an overall market preference. The results from this market analysis are given in the Table 3 below.

Table 3: Market preference for various competitions

Market Preference		Boeing					
		B737		B737MAX		Next B737	
Airbus	A320	49%	51%	21%	79%	23%	77%
	A320E	56%	44%	34%	66%	31%	69%
	A320NEO	71%	29%	49%	51%	56%	44%
	Next A320	70%	30%	41%	59%		

Several observations may be drawn from these results:

- The current state of the market is represented by the A320 versus B737 competition and yields a 49% to 51% market preference. This is surprisingly close to what is observed.
- The enhanced A320 and the re-engined A320 show increasing market preference over the baseline A320 when competing against either the B737 or the B737MAX due to an increase in fuel efficiency.
- Similarly, the re-engined B737MAX has a better market penetration than the baseline B737 when competing against the A320, enhanced A320 and A320NEO due to an increase in fuel efficiency.
- The competition is asymmetric because the re-engined B737 enters the market two years after the re-engined A320 and therefore benefits from improved efficiency and improved technology maturity.

- The development of clean sheet designs (represented by the Next A320 and the Next B737) does not pay off in terms of market preference. Indeed, even though airlines are saving from increased fuel efficiency, maintenance efficiency and reduced emissions, this is not sufficient to offset the higher acquisition premium.

In summary, the market penetration of each aircraft design proposed to the airlines yield results that are in agreement with what is observed on the market (or projected) and paves the way for the profitability assessment of each aircraft development program.

7 Staggered Investment Viability Analysis

With preliminary estimates of the market reaction to new products, it is possible to investigate the profitability of these development endeavors. Profitability data and R&D costs are not usually available in the public domain. This is why the rank-order statistics of the profitability estimates is more relevant than the actual number. The development costs and timeline, the sales prices as well as the profit margin used for the different aircraft are provided in Table 4.

Table 4: Aircraft development costs and timelines

Aicraft Development Program	Price (M$)	Profit Margin	Phase 1 Start	Phase 1 Cost (M$)	Phase 2 Start	Phase 2 Cost (M$)	Entry Into Service
A320 Continuous Improvements	45	6%	2010	1	2011	4	2012
A320E	46	6%	2010	20	2011	50	2013
A320NEO	55	6%	2010	1 000	2015	1 500	2016
Next A320 - V1 Next A320 - V2	65	6%	2019 2015	3 000	2024 2019	7 000	2025 2020
B737 Continuous Improvements	45	6%	2010	1	2011	4	2012
B737MAX	55	6%	2011	1 500	2016	2 500	2018
NextB737 - v1 Next B737 -V2	65	6%	2019 2015	3 000	2024 2019	7 000	2025 2020

It is assumed that the development is articulated around three major phases each separated with a milestone. The first phase is the design, the second phase is the testing and certification, and the last phase is the production. At the end of the first phase, the aircraft program may be cancelled if it is likely that the program will not be successful. After this milestone, it is hypothesized that the program will continue because most of the development hurdles and costs have already occurred. Using the real-options methodology described earlier, the profitability of each program is assessed and the results are provided in Table 5.

Table 5: Program profit for each scenario

Program Profit (M$)	A320	A320 "E"	A320 NEO	Next A320	B737	B737 MAX	Next B737
Scenario 1	2 700	4 900	18 000		8 200	10 400	
Scenario 2	7 000		18 500		9 000	10 400	
Scenario 3	2 700	10 100		1 200	9 200	13 700	
Scenario 4	11 000		7 400		10 100	13 400	
Scenario 5	12 400			10 300	13 000		10 300

These program profits are then aggregated for the two suppliers to yield an overall scenario profit. The rough profit estimates are then replaced by the rank order statistics and displayed in Fig 8.

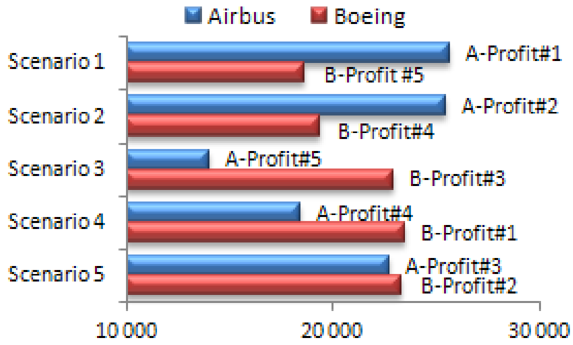


Fig 8: Rank order of manufacturer profits

Using these results as well as the decision tree presented in Fig 9, the Nash Equilibrium represented by Scenario 1 becomes apparent when Airbus is the first mover of the game. Indeed, for this particular scenario, no competitor has any incentive to deviate, and choosing a different course of action would not result in equilibrium. It is interesting to realize that Scenario 1 reflects exactly the set of strategies selected by Airbus and Boeing.

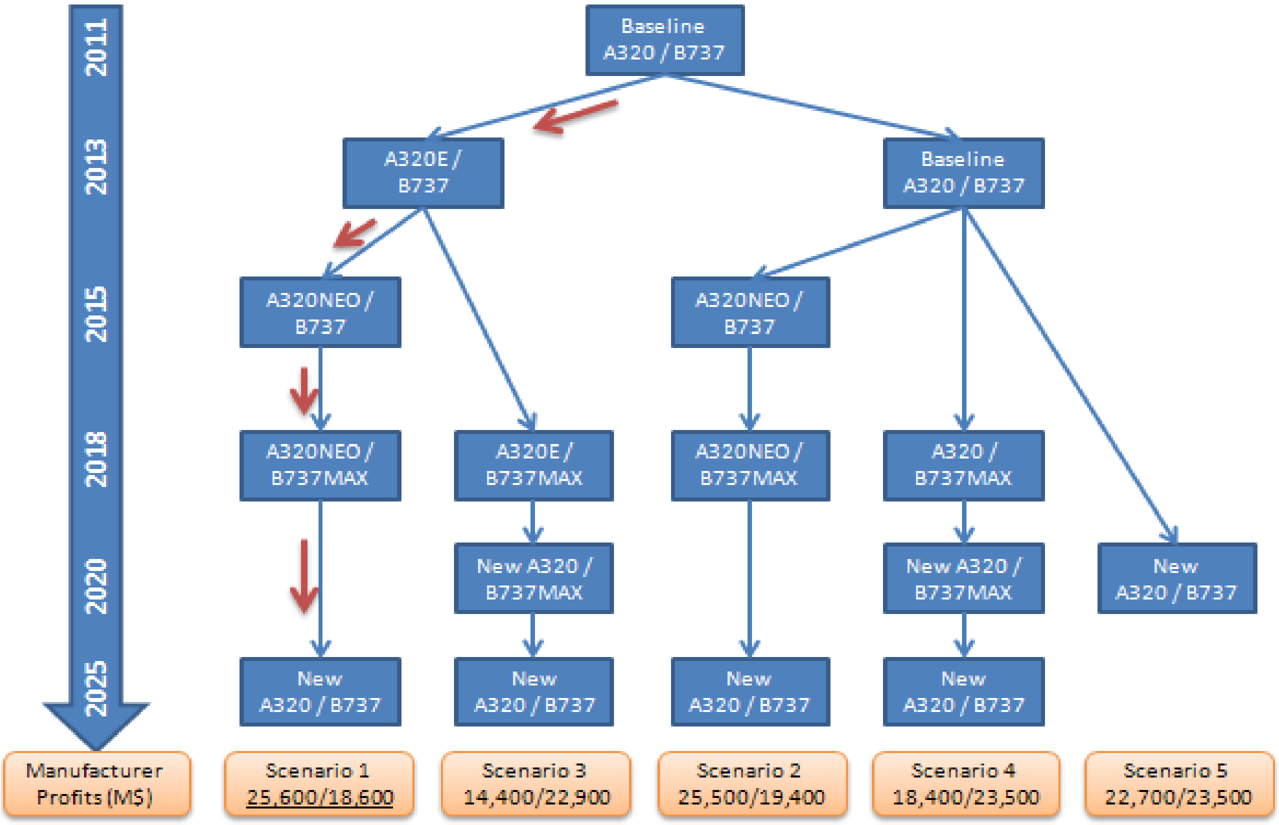


Fig 9: Decision tree with payoff for competitive environment under investigation. Nash equilibrium is highlighted

The same profitability analysis is carried out without modeling the carbon emission tax and achieves similar results. This indicates that the carbon taxation has little impact on the strategies of aircraft manufacturers.

8 Conclusion

In this research, a methodology for the economic analysis of a commercial aircraft development program is proposed. The methodology incorporates elements from real-options analysis to capture the value of flexibility, as well as a game-theoretic approach to account for the competitive interactions. The proposed methodology is applied to the upgrade and subsequent replacement of narrowbody commercial aircraft and provides insights as to the strategic decision made by both Airbus and Boeing. The results are in agreement with observations from the industry and show that the inclusion of carbon emission taxation during the aircraft valuation has little impact on airline fleet purchase decisions. Improvement of the current methodology includes the modeling of learning curve effects and their impacts on the profitability of manufacturers.

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