FINDING THE REAL VALUE OF ADAPTABLE VEHICLE CONFIGURATIONS IN AN UNCERTAIN WORLD

Ismael Fernández, Prof. Dimitri N. Mavris
Aerospace Systems Design Lab, Georgia Institute of Technology
Atlanta, GA 30332

Keywords: *Adaptability, Real Options, Strategy, Decision-Making*

Abstract

The focus of many aerospace design methods today is on finding a robust solution that can successfully perform its mission under a variety of scenarios. In most cases, there is a trade-off between robustness and optimality. Robust designs may become far from optimal for today's conditions and quite suboptimal for future requirements. The issues of architecture selection and final design configuration also become a problem when forecasts of profitability and market preferences cannot be very accurate. The authors lay out a method, using Real Options valuation, to find solutions that while closer to optimum for today's conditions, are capable of adapting to new scenarios in the future. This method also provides the real monetary value of such adaptable configuration, and introduces decision- making rules and visual aids for architecture selection.

A sample case scenario, regarding the development of a supersonic business jet, demonstrates the usefulness of this method when facing an important design decision. It has been found that completely different strategies may lead to the same payoff. Therefore a firm pursuing an adaptable design should consider the most cost efficient path to obtain the same adaptability.

1 Introduction

Aerospace Design Methods are becoming more management and economic conscious. The proliferation of tools such as Game Theory, Neural Networks, and Real Options indicate the need for including strategic decision-making early at the design stages. Each day it becomes more important to forecast the final return on investment, and the relative status with respect to competitors. Because we now live in a global economy, the size or reputation of a corporation has become less relevant. In exchange, what is now important is the final benefits to customers, their time frame, and their risks.

In the aerospace industry, a global one indeed, the situation is no different. Developing countries, such as India, are forming new airlines. Airline needs are now changing rapidly from market to market. For instance, the needs of a legacy airline in the US are different to the needs of a new carrier in China. These differences play a big role in decision-making when designing new vehicles, and the tremendous impact they have today on profitability makes them quite important. It is also crucial to understand that design decisions, most of the times, are final and irreversible; because of this, it is necessary to cope with uncertainty in the future and to predict the consequences of decisions with some degree of confidence.

Currently many firms see change and uncertainty as synonyms of risk. Unexpected change is always risky but with preparation this may also become an opportunity. In fact, preparation for change is the idea behind the new wave of decision-making tools such as Real Options or Game Theory. This paper tackles the issues with design configuration decision-making in aerospace vehicles, and outlays a process by which design engineers can observe value, optimum decision points in time, and strategies to cope with change by using Real Options concepts.

Real Options is an option pricing technique used in management to predict the value of real assets when facing uncertain scenarios. Here by real we mean non-financial assets, such as new firms, licenses, projects, etc. This technique is however directly taken from the financial world.

One of the efforts of current design methods, given by the design paradigm shift, is on holding more freedom during the design process [1]. The monetary value of this freedom, which can be measured by the flexibility of a design, can be assessed by these option pricing methods. In addition, option pricing allow designers to become more aware of the value of having choices, and the consequences of their decisions. A perfect example of the need for adaptable designs is the development of morphing aircraft structures. This technology may optimize the airfoil and geometry of a wing for a specific mission while in flight. The value of this technology is therefore a function of the adaptability it provides and the variety of missions that will be able to perform.

This paper defines the concept of design for adaptability; it proposes a method for obtaining the real monetary value of an adaptable design based on the uncertainty surrounding the performance requirements, and at the end, presents a sample problem that demonstrates the usefulness of this method when making a selection between two different architectures.

2 Designing for Adaptability

Decades ago, the focus of engineering was to obtain an optimum technical solution that could perform exactly as required in the most efficient way. New methods became available with the introduction of quality control, through the loss function, and the availability of probabilistic analysis to analyze external factors as well as possible future requirements. These new methods, enabled by available computational power, now focus on viable and feasible solutions that perform as expected under many circumstances.

One of the drawbacks of this approach is the possibility of leaving technical capabilities on the table. In some cases a robust design has to give up some optimality to perform correctly under a wide range of conditions, lowering the probability of success (P of S) of the system. Notice the differences between Optimum and Robust given in Fig. 1. This paper defends the concept that the focus of engineering efforts should include the search for adaptability. Adaptable designs do not push for better efficiencies or technologies but for more flexibility to the customer. The probability of success of an adaptable design, given today's conditions, is slightly lower than an optimum solution, however, the fact that it can adapt to new market trends, makes it more valuable.

The author lays out a technique that attempts to obtain solutions that are closer to optimum, adaptable, and provide the firm with maximum return while minimizing risks. This would ensure that optimality is maintained under new circumstances. Refer to Loss Function comparison in Fig. 1.

Potential benefits of this approach include an increase of financial returns, and a better understanding of a firm's risks. Consequently a firm would be able to save more capital for R&D on new technologies.

3 Method

The proposed method addresses the issue of combining technologies and architectures, by evaluating the impact on the capacity of the final system to adapt to new conditions as these evolve. The process of obtaining the real value of an optimum vehicle and its adaptability is the following.

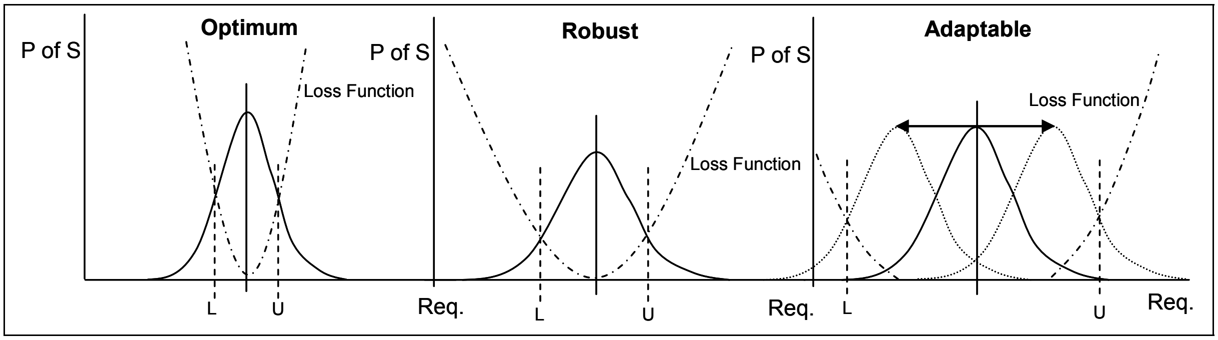

Fig. 1. Comparison of Design Approaches

First, the method starts with a preliminary design process in which meta-models, approximation models in place of high-fidelity codes, provides the designer with a set of feasible solutions. Second, these designs are then refined according to a set of economical requirements and constraints to ensure their viability. The process then filters all design possibilities by using a Pareto optimality approach. Third, a model based on scenario analysis helps to predict the change of customer preferences over time. Real Options analysis uses this model to obtain the value of adaptability. Finally, a rapid assessment of expected returns and inherent risks help us to identify a solution and a strategy that maximizes the ratio of return over risk.

3.1 Stage I: Production of Preliminary Solutions

During the first stage of this method, the focus should be on building a model where engineers can rapidly evaluate the validity of different design alternatives. The designer may select a configuration by using a morphological matrix as outlined in references [3]. This configuration is then modified by using the already mature Robust Design Simulation method. This method combines the use of Monte Carlo simulation with meta-modeling techniques such as Response Surface Equations or (RSE) to rapidly obtain thousands of designs with each configuration in little time. Several references provide more details on these techniques and their benefits [1, 2, 3, 4, 5]. As a result of this process, the design engineer has the opportunity to observe the design space, and eliminate those areas in which designs violate the constraints.

There are three different types of constraints that require careful consideration. First, customer requirements may be presented as constraints. Even though in many cases these constraints may be flexible, for certain metrics, the customer will not be willing to accept a design that does not meet certain criteria. Secondly, to stay competitive in the market place, a new design has to be at least as good as the latest release of a similar system. This requirement in essence is the need for technology evolution. In reality new products have to be better than existing ones, but when setting constraints we need to make sure that at the very least no performance metric is worse than any of the other alternatives. Finally, it is also important to observe the regulatory requirements, since it is imperative that the system in hand performs according to current and future policies. These three types of constraints have something in common. They all evolve with time but none are controlled by any single player, and are measurable. These characteristics are crucial for implementing the scenario and Real Option analyses later in the process.

A final selection of the remaining solutions should take place after eliminating the designs that do not meet the constraints. With the new data in hand, and thanks to the available computational power, it is possible to obtain a set of non dominated solutions by using a Pareto frontier. These solutions cannot improve in any metric without penalizing another one. Roth et al explain in greater detail the concept of Pareto frontiers and its benefits [6]. Fig. 2 depicts a sample Pareto plot of two metrics. The consideration of these solutions is important because every solution from this point on becomes technically optimum for a specific scenario. The next step in the process is to obtain a first look at the financial numbers to compare alternatives that maximize the return to the developing firm.

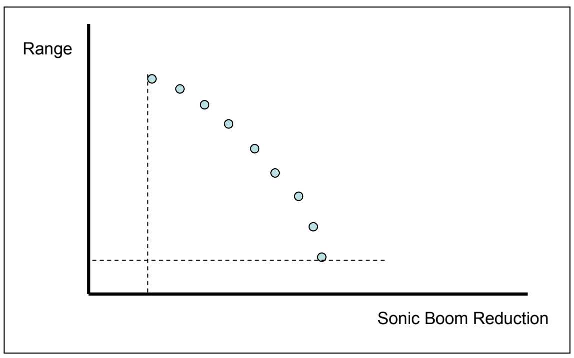

Fig. 2. Sample Pareto Plot

3.2 Stage II: Financial and Scenario Analysis

A rapid economic assessment based on the life cycle cost and future profitability of the designs takes place after this initial design simulation and selection. A financial model, mainly based on traditional accounting principles and discounted cash flow, provides the decision-maker with profitability numbers for the client and the system manufacturer. Careful consideration needs to be given to technologies since in some instances the benefits of adding a new technology does not justify the extra cost of development.

With all this information in hand, it is possible to start looking at adaptability options, their real value, and how to design them. To assess the value of adaptability we start by looking at the potential losses incurred by a faulty design; a design that becomes suboptimum after a change in requirements or preferences. One way to obtain this is by constructing a *loss function*. The loss function is the solution of a Monte Carlo simulation in which external factors, affecting the preferences, randomly evolve with time, affecting the total demand for different architectures, and therefore the payoff of each alternative.

Finding the loss function is a critical portion of the valuation process. Having the capability of shifting a design from one optimum solution to another, when conditions require it, reduces the loss function to zero. An inflexible design does not allow a firm to manage its future, making profits fluctuate without control over time. If it is possible to modify a design to take advantage of uncertainty, a firm can benefit from the loss function in the form of a positive payoff. The loss function becomes a payoff function because an adaptable design allows for changes necessary to avoid losses.

Obtaining the pay off function is the most critical steps on option valuation. In essence the payoff function is the result of a scenario analysis in which each of the optimum technical solutions also become optimum financially under different conditions. For the scenario analysis to be fully complete, changes in external factors, affecting the decision-making process of the end user, as well as the three types of constraints mentioned earlier, should be simulated over time.

Ideally, adaptable designs will eliminate the loss function in a range of conditions by adapting the design when necessary without the need for developing new systems as shown in Fig. 1. The size of this range affects the amount of R&D resources needed to cover the adaptability needs. As the range widens, the cost of developing an adaptable design increases significantly. Picture the cost of designing a vehicle that can change shape while in flight from an optimum extreme in the Pareto plot to another. This would not only be cost prohibitive but also the value of that adaptability will most probably be well below the implementation costs.

3.3 Stage III: Valuation of Adaptability

Adaptability is the capability to change when there is a need for it. In engineering, having an adaptable design is now important to ensure the success of the system throughout the life cycle. The flexibility provided by adaptable designs is similar to the one that stock options provide its holders in the stock market. While an option allows its holder to exercise at a predetermined price, adaptability enables the modification of certain characteristics of a design at a minimal cost when conditions require it.

Option valuation in the context of real assets, such as manufacturing plants, patents, projects, or else, has a different name, Real Options Analysis or ROA. The main focus of ROA is to actively manage real assets to ensure that risk is mitigated while opportunities are seized when facing uncertainty [7]. This aspect of Real Options is not useful to design engineers in its entirety because of the little impact that managerial decisions may have on the vehicle preliminary design. Same valuation principles however may be used at the engineering level to obtain the value of designs that are adaptable to different scenarios. Wang and de Neufville refer to the difference between pure managerial Real Option problems and engineering problems [8]. Some research has been performed in implementing Real Options at different design stages in aerospace [9].

3.3.1 Obtaining the Value of an Option

Options, alternatives, or decisions can be evaluated by their possible outcome in different scenarios. A good decision is such that produces a positive outcome under any circumstance. Most of the times, however, outcomes may be either positive or negative with uncertainty. Because of this, it is very common to find value for instance on waiting until more information is available before committing to a choice. Obtaining the value of an option is not a complex process, but it is not intuitive at first.

There are several methods for obtaining the value of an option. A common way is the Black-Scholes method that uses a closed-form solution of a partial differential equation outlined on [15, 16, 17]. This method turns out to be exact and fast in finance, but the underlying assumptions are not reasonable for engineering analysis. A second method, widely used in finance as well, is a numerical approximation performed through binomial lattices or trees. This approach becomes very accurate when the size of the tree, given by the number of steps, increases significantly. In fact it approaches the exact solution as the number of steps approaches infinity. In addition, this method becomes of great use in engineering analysis because all the assumptions are accessible. Fig. 3 depicts an example of a two-step binomial tree.

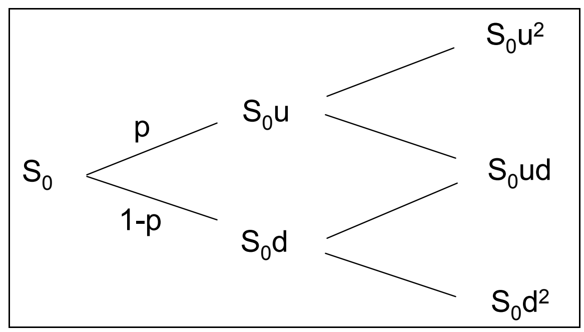

Fig. 3. Binomial Tree

The tree displays two steps of the values that the underlying variable (S_0) might take over time until a decision has to be made at the last period. This variable might be a requirement, a trade-off setting, or even a project's profitability. A basic assumption here is that the value of the underlying variable at the next period may only go up or down. The volatility, a metric that predicts the amount of variability of the underlying value over time, sets the values of multipliers (u) and (d). The probability that S will go up by next period is depicted by (p). Mun provides different methods of obtaining the volatility by using either Monte Carlo simulations or historical data regressions [15].

Population of the tree occurs by multiplying the underlying value by the up and down factors repeatedly, as described by the figure, above until expiration on the right.

The model then evaluates the payoff function at expiration. This payoff function is in essence the value of the adaptability option at expiration. The following method focuses on obtaining the value of that adaptability today by considering the time value of money, and the probabilities of different outcomes. To do this, the model takes two adjacent values at expiration and computes the expected value of the outcome using the probabilities of each outcome. This is then discounted in time to obtain the value at the previous step. The following equation summarizes the computations.

$$OptionValue = (p(S_0 u) + (1-p)(S_0 d))e^{-rf\delta t}$$

where *(rf)* is the risk free interest rate, and *(δt)* is the duration of each step. The computation of this equation on all nodes repeatedly, from right to left, yields the monetary value of the adaptability option today. Finally, by observing the *time value*, or the portion of option's value that is associated with the value of waiting, it is possible to build a tree that assesses the decision-making at each period. The real value of an optimum configuration (e-NPV) is then found by adding the value of the option, or adaptability, to the NPV while subtracting the cost of implementing the option. A decision should be made when two main conditions occur:

- First: time value is zero. If there is value on waiting, the outcome of an early decision might be negative; therefore an option should never be exercised early.
- Second: the value of the adaptability under consideration should be above the cost of implementing it. This condition ensures that an adaptable design will provide a positive financial outcome. To assess this condition it is necessary to think about different ways of implementing adaptability and forecast their respective costs. Two different ways to tackle this issue are infusing certain technologies on a baseline, or designing other alternatives simultaneously knowing that one of them will be discarded. It is important to keep in mind that the process in hand performs a valuation based on the variation of future profitability and not on the cost of new technologies.

A simple comparison of alternatives can be carried out by using the ratio of extended NPV (e-NPV) to the difference in maximum and minimum benefits given by the scenarios. The following section illustrates this method by using a notional case involving the development of a supersonic business jet.

4 Sample Case

The design of a supersonic business jet is currently undergoing. One of the most fundamental needs for the success of this vehicle is to achieve a low sonic boom overpressure for supersonic flights over land. If a decision is made, certification is planned to start in ten years, so the final design would have to be ready by the sixth year. The design team is facing a situation that needs immediate attention. The issue is that sizing the vehicle for a low sonic boom will impact other metrics. Fig. 4 displays an optimum configuration and geometry for sonic boom suppression [12].

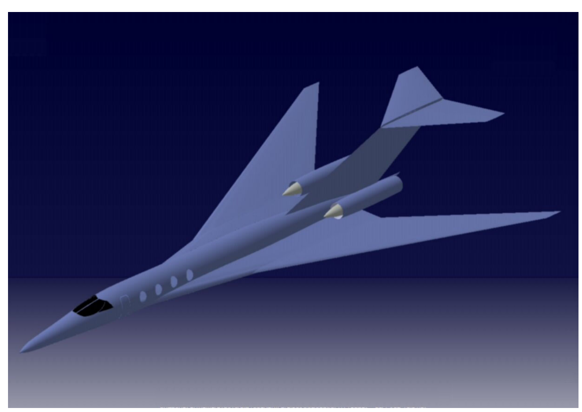

Fig. 4. Sample Quiet Supersonic Jet

Smaller airplanes produce less sonic boom overpressure than larger aircraft. However, reducing the size of the aircraft will have a negative impact on range, payload, cabin noise, and other metrics such as comfort.

The preliminary design group confronts the question of whether their emphasis should be made on reducing the sonic boom to accommodate the need to fly supersonic over land, on sizing the plane for long trans-oceanic routes with comfort, or on finding a compromise solution. Even though this type of decision is mostly strategic, and most of the times addressed at the managerial level, it can be tackled at the engineering level using real options valuation techniques, financial models, and some market analysis. The following assumptions are necessary to better frame the problem. First, the level of demand is only dependent on external factors affecting the end users only. Second, there is no available alternative in the market place. Third, all the other technical requirements can be met with any architecture under consideration. Also, a somewhat accurate market survey has been carried out recently, and a model reflecting preferences based on uncontrolled factors has been developed. With these assumptions in mind we can start the process by identifying three possible architectures.

4.1 Obtaining Technical Solutions

The use of meta-modeling techniques such as Response Surface Methodology (RSM), in conjunction with optimization methods like sequential linear programming, helps to obtain optimum alternatives in each case. Further explanation of the methods for obtaining these solutions is available through [12]. Fig. 5 shows a sample Pareto frontier with the best alternatives. The first alternative (A) has optimum range, while alternative (B) is sized for minimum sonic boom. A third alternative, a compromise solution between the former two, is also available; (C).

4.2 Financial Analysis

The problem with the compromise solution (C) is that it does not fully satisfy the needs for either mission. Its sonic boom is probably high enough to ban it from flying over land, and its range is not optimum enough for long trans-oceanic flights. The demand of designs (A) or (B) is a direct function of the external factors that affect the needs to fly supersonic overland.

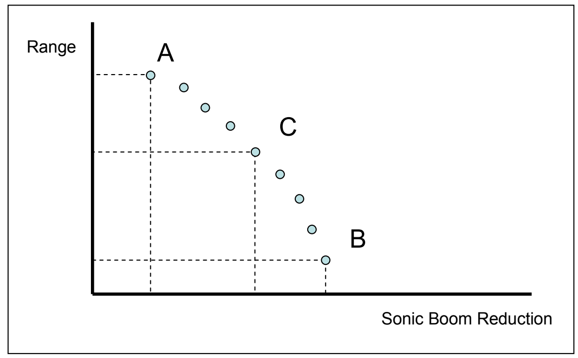

Fig. 5. Supersonic Business Jet Alternatives

If these factors push for a need to fly supersonic over land, the production of the quiet alternative (B) will have a better payoff than the long range supersonic cruiser (A). Because external factors evolve randomly over time and are independent of each other, we need to compose a model that takes into consideration these factors into a single decision metric. The construction of this model will be beneficial, not only to assess the current market preference, but also its variability with time. This metric will be a measure of the percentage of the market that is inclined to purchase one design versus the other. The measure of that metric today is 0.3, meaning that today only 30% of the market prefers the quiet design. If it reaches a value of 1.0, one hundred percent of the market will prefer the quiet alternative. The opposite is also true. Because external factors evolve without control, the behavior of this decision metric is also stochastic in nature. The payoff function is constructed by performing traditional finance calculations based on costs and revenues from the number of sales. Fig. 6 shows the profitability of alternatives (A) and (B), according to the Net Present Value or (NPV) as a function of market preference.

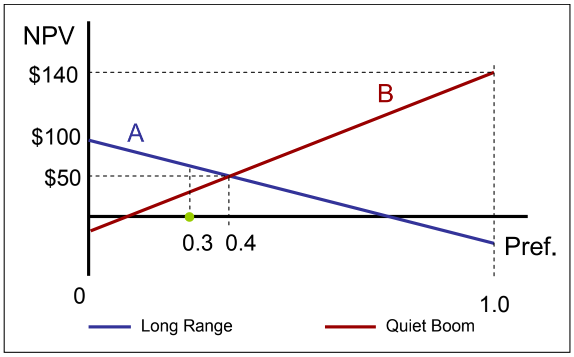

Fig. 6. NPV with alternatives

If the current preference is below the intersection at 0.4, the long range solution will provide better benefits because more than 60% of the market would prefer a long range version. At the intersection both alternatives are equally profitable, while the quiet design becomes more profitable beyond the intersection point.

4.3 Valuation of Adaptability

The firm facing this situation has the possibility to pursue three different strategies:

1. Invest on the long range alternative. Given the current situation, only 30% of the market demands the quiet aircraft, the payoff is higher with the long range solution.
2. Invest on the long range alternative and the option to adapt to low sonic boom design.
3. Invest on the low sonic boom design and the option to adapt to a long range solution.

Fig. 7 displays these strategies on the Pareto frontier, the first strategy is a gamble. Even though with lack of competition at this time, making the wrong choice early may provide advantages to potential entrants. In addition, investing on a fix design would only be worth pursuing with no uncertainty at all. Because this is not the case, we will explore the second and third strategies and compare the results to those of strategy one under several scenarios.

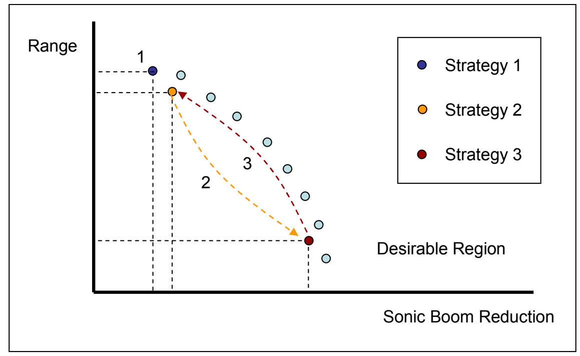

Fig. 7. Layout of Strategies

To assess strategy two, the first step is to build the payoff function. This is the benefits obtained by having the ability to switch to the low sonic boom design at any time before a final decision has to be made. Exploring Fig. 6 one realizes that if there is no value on switching to the quiet design as long as the preference value is below 40%. Therefore from zero to 0.4, the payoff of the adaptability option is zero. Beyond 40%, the value of this adaptability becomes the difference between the NPV's of the two designs. The value of the adaptability option, with time value and at the time of expiration is depicted in Fig. 8. The value of having this adaptability is then calculated by using the Binomial Tree described earlier.

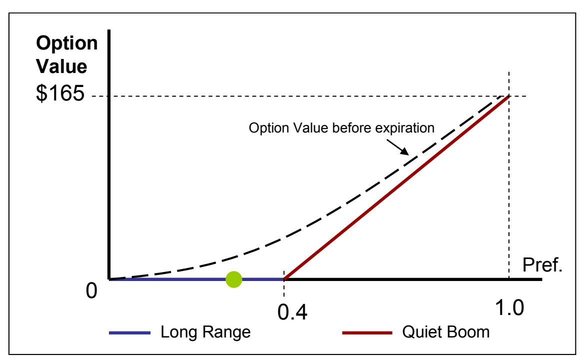

Fig. 8 Payoff of Option to switch to B

Fig. 9 below displays the Binomial Tree used for this computation. For simplicity, the tree shows six periods corresponding to six years; the tree could be thousands of steps long for accuracy, but by reducing the size of the time step (δt) as mentioned in the equation above.

It was assumed that the volatility of the preferences is at 16% per year. During this time the preference for a quiet jet versus a long range alternative may increase up to 78% of customers, or decrease to a minimum of 11%. These values are displayed within the gray cells.

Period	0	1	2	3	4	5	6
							78%
						0.67	105.46
					0.57	73.61	57%
				0.48	46.46	0.48	46.46
			0.41	27.65	0.41	23.33	41%
		0.35	15.84	0.35	11.63	0.35	3.61
	30%	8.82	0.30	5.76	0.30	1.66	30%
	$ 4.81	0.26	2.84	0.26	0.76	0.26	0.00
		1.39	0.22	0.35	0.22	0.00	22%
			0.16	0.19	0.00	0.19	0.00
				0.00	0.16	0.00	16%
					0.00	0.13	0.00
						0.00	11%
							0.00

(gray) % of Preference for B
(white) $ Value of Option

Fig. 9. Binomial Tree with value of Option

The value of the adaptability option is below the preference numbers. The value of this option today, $4.81M, was obtained by using the backward induction process mentioned in section 3.3. The value of strategy 2 then becomes the value of the NPV today, $62.5M, plus the value of this adaptability option, $4.81M, less the value of purchasing this option which is still unknown. The name of this new variable is e-NPV or extended NPV.

After analyzing strategy 3 in the same way, it was surprising to find that the value of the option to switch to a long range design was $32.31M. The NPV of starting the low sonic boom design however is almost half the NPV of Strategy 2, $35M. What is surprising about this is that when calculating the e-NPV, both strategies, 2 and 3, produce exactly the same benefits of $67.31M. This has proven to be true for any scenario. The model proves that the value of adaptability is completely independent from the strategy taken to achieve it. Two main questions remain after calculating the value of adaptability. Firstly, what strategy should the firm choose given that both of them provide the same value? Secondly, when is the optimum time to make a decision on implementing the option? How can we make sure that the strategy that we chose will provide the best benefit of all?

The first question is easy to answer. The strategy that a firm should follow is the most affordable one. In this example, from the engineering point of view, it seems easier to design a small vehicle with the possibility of carrying external fuel tanks for longer missions than designing a large vehicle with immature technology that may or may not meet the maximum sonic boom pressure allowed in the future.

Option valuation will indicates when it becomes optimum to make a final selection, or in other words, when the value of waiting vanishes. This may happen before expiration, when the volatility is small enough to ensure only one outcome. The following tree was constructed by evaluating the time value at every node. The time value again is the difference between the value of the option at a particular point in time, and its value at expiration. If the time value becomes zero, it means that the uncertainty is not big enough to justify adaptability; therefore a decision should take place. Surprisingly again, the decision binomial tree, depicted in Fig. 10, is exactly the same for strategies 2 and 3.

This turns out not to be a coincidence, and validates the idea that the method obtains an accurate measure of adaptability independently from the strategy taken.

Period	0	1	2	3	4	5	6
							0.78
						0.67	QSJ
					0.57	QSJ	0.57
				0.48	QSJ	0.48	QSJ
			0.41	Wait	0.41	QSJ	0.41
		0.35	Wait	0.35	Wait	0.35	QSJ
	0.30	Wait	0.30	Wait	0.30	Wait	0.30
	Wait	0.26	Wait	0.26	Wait	0.26	LRSJ
		Wait	0.22	Wait	0.22	LRSJ	0.22
			Wait	0.19	LRSJ	0.19	LRSJ
				LRSJ	0.16	LRSJ	0.16
					LRSJ	0.13	LRSJ
						LRSJ	0.11
							LRSJ

QSJ Quiet Super. Jet
LRSJ Long Range S. Jet
(gray) % of Preference for B
(white) Best Action

Fig. 10. Binomial Decision Tree

To finalize this process Table 1 shows the results of a final scenario analysis that evaluates the profitability of these three strategies under several scenarios as measured by e-NPV. Because of the low maturity of sonic boom suppression technologies it was assumed that the cost of Strategy 2 was in the order of $20M. Strategy 3 however is more feasible, so a cost of $5M was input in the model.

Table 1. Results from Scenario Analysis

Scenario Analysis

e-NPV's

Scenario 1: Forecat was correct		30%
Strategy 1	$62.50	
Strategy 2	$47.31	
Strategy 3	$62.31	
Scenario 2: Quiet Boom Prefered		70%
Strategy 1	$12.50	
Strategy 2	$76.98	
Strategy 3	$91.98	
Scenario 3: Long Range Prefered		15%
Strategy 1	$81.25	
Strategy 2	$61.25	
Strategy 3	$76.25	

Strategy 3 includes features from 1 and 2. It has the benefits of obtaining high payoffs in all cases, it becomes best during scenario 2, and its profitability closely match the one of Strategy 1 in other cases. Strategy 3 is the solution that provides the highest benefits (e-NPV) with the least amount of variation across scenarios. This fact is quickly depicted by looking at Fig. 11. It is therefore recommended to invest research and development efforts into a relatively small quiet supersonic business jet which range can be expanded to accommodate current demand issues.

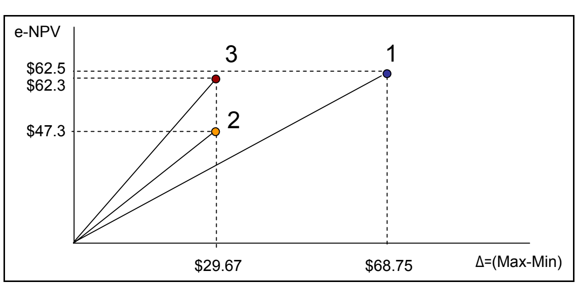

Fig. 11. e-NPV vs. Volatility

If the legal battle over supersonic flight over land turns out favorable, the design would be ready to sell immediately, setting the corporation into a very competitive position.

5 Conclusions

New engineering methods that include non-engineering aspects are on the rise. Real Options analysis combined with financial codes provide a framework to integrate the economic aspects of a design at the development stages. The presented method provides the design team with a better understanding of the impact that design decisions have in the future profitability of the firm under different scenarios. It also achieves several important goals. First, it helps to identify the benefits of making a design more adaptable rather than more technologically advanced. Second, it asses the real value of such adaptability, which later can be benchmarked against the cost of implementing it. Finally, it provides decision-makers with a visual solution that highlights optimum decision points. It also shows the value inherent on waiting to commit. The option valuation method has been validated using a sample case scenario in which some assumptions bounded the problem for simplicity. Further investigation is currently ongoing to expand the range of possibilities and validate these techniques in a wider set of conditions. Among the extensions already available to this model are: the consideration of cost of waiting, and the inclusion of a larger number of alternatives.

References

[1] Myers, R.H., *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*, John Wiley & Sons Inc., 1995

[2] Mavris, D.N., Baker, A.P., Assessing the Simultaneous Impact of Requirements, Vehicle Characteristics, and Technologies during Aircraft Design. *39th AIAA Aerospace Sciences Meeting and Exhibit,* Seattle, WA, 2001

[3] Mavris, D.N., DeLaurentis, D.A., Bandte, O., Hale, M.A., A Stochastic Approach to Multi-disciplinary Aircraft Analysis and Design, *36th Aerospace Sciences Meeting and Exhibit,* Reno, NV, January 12-15, 1998.

[4] Mavris, D.N., Bandte, O., A Probabilistic Approach to Multivariate Constrained Robust Design Simulation, SAE Technical Paper 97-5508

[5] Mavris, D.N., Bandte, O., 1997 A Probabilistic Approach to Multivariate Constrained Robust Design Simulation, *Presented at the 2nd World Aviation Congress and Exposition*, Anaheim, CA, October 13-16, 1997.

[6] Roth, B., Graham, M., Mavris, D., Macsotai, N., Adaptive Selection of Pareto Optimal Engine Technology Solution Sets, *Presented at the 2002 ICAS Conference*, Toronto, ICAS2002-5.9.4

[7] Hull, J. 2003. *Options, Futures, and Other Derivatives*. 5th ed., Upper Saddle River, NJ: Prentice Hall

[8] Wang, T., de Neufville, R., Real Options "in" Projects. *9th Real Options Annual International Conference.* Proceedings of a conference organized by the Real Options Group and held in Paris in June of 2005

[9] Suh, E.S., de Weck, O., Kim, I.Y., Chang, D., Flexible Platform Component Design under Uncertainty. *Journal of Intelligent Manufacturing*. Special Issue on Product Family Design and Development. Revised Draft. March 15-2005

[10] Miller, L., Bertus, M. 2005. License Valuation in the Aerospace Industry: A Real Options Approach. *Review of Financial Economics*, 14(3-4):225-239

[11] Saleh, J.H., Hastings, D.E., Newman, D.J. Flexibility in Systems Design and Implications for Aerospace Systems. *Acta Aeronautica*. 2003, 53 (12) 927-944

[12] Banerjee, P., de Weck, O.L. Flexibility Strategy – Valuing Flexible Product Options. INCOSE/ICSE *Conference on Synergy Between Systems Engineering and Project Management*, Las Vegas, Nevada, September, 2004

[13] de Weck, O., de Neufville, R., Chaize, M. Staged *Deployment of Communications* Satellite Constellations in Low Earth Orbit. *Journal of Aerospace Computing, Information, and Communication,* 1(March) 119-136

[14] Weeds, H. Strategic, 2002. Strategic Delay in a Real Options Model of R&D Competition. *Review of Economic Studies*, 69(3), 729-747

[15] Howell, S., Stark, A., Newton, D., Paxson, D., Cavus, M., Pereira, J., Patel, Kanak. 2001. *Real Options Evaluating Corporate Investment Opportunities in a Dynamic World*. London: Prentice Hall

[16] Mun, J. 2002. *Real Options Analysis: Tools and Techniques for Valuing Strategic Investments and Decisions*. Hoboken, NJ: John Wiley & Sons, Inc

[17] Ruppert, D. 2004. *Statistics and Finance. An Introduction*. New York: Springer-Verlag

[18] Briceño, S.I., Buonanno, M.A., Fernández, I., Mavris, D.N. *A parametric exploration of Supersonic Business Jet Concepts*. Presented at the 2nd AIAA ATIO Forum, Los Angeles, CA, October 1-3, 2002.

Authors

Ismael Fernández
Aerospace Systems Design Lab
Georgia Institute of Technology, Atlanta, GA 30332
ismaelf@asdl.gatech.edu

Prof. Dimitri N. Mavris
Director of Aerospace Systems Design Lab
Georgia Institute of Technology, Atlanta, GA 30332
Dimitri.mavris@ae.gatech.edu