

**A FRAMEWORK FOR VALUE-DRIVEN AIRCRAFT FAMILY  
DESIGN FOR DYNAMIC MARKET SYSTEMS UNDER  
UNCERTAINTY AND STRATEGIC COMPETITION**

A Thesis  
Presented to  
The Academic Faculty

by

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In Partial Fulfillment  
of the Requirements for the Degree  
Doctorate of Philosophy in the  
School of Aerospace Engineering

Georgia Institute of Technology  
December 2016

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*To my parents and sister*

## ACKNOWLEDGEMENTS

One of my childhood dreams, getting a PhD in Aerospace Engineering from a top school, would not become a reality without the infinite patience and support of Prof. Dimitri Mavris. Meeting him in Turkey changed my life in every possible way as he became my second father. He didn't only lead me explore parametric design spaces and develop designs but also explore my personality and develop myself both personally and professionally. This was a rough road with lots of unexpected incidents but his guidance helped me navigate through the storm. His brainchild, Aerospace Systems Design Laboratory, gave me a head-start to my career during which I will always be proud to be the student of the Greek philosopher.

I would also like to thank my committee members: Prof. Schrage, Prof. Vicentini, Prof. Ozturk, and Dr. Pfaender for their support and feedback. Other than his committee support, it was a pleasure for me to work with Dr. Pfaender on the Environmentally Responsible Aviation project sponsored by NASA. I learned a lot from Prof. Schrage both during our NASA rotorcraft competition and via the classes he taught. Late addition of my external committee members Prof. Ozturk and Prof. Vicentini's support and feedback were crucial as my research was a cross-fertilization of aerospace engineering and economics and they helped me keep up with the new developments in the areas of competition and market entry.

I formed numerous friendships during my time in Georgia Tech especially in ASDL, Turkish Student Organization, and other fellow yellow jackets. Abundance of research ideas, freedom, and select people from diverse backgrounds in ASDL trigger formation of many different interdisciplinary studies and I enjoyed long intellectual conversations with many of my peers. Turkish Student Organization was a touch of home in Atlanta whenever I needed. I also made a lot of friends in various sports clubs and especially cycling on the roads of Georgia.

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## NOMENCLATURE

<b>ACQ</b>	Acquisition Cost
<b>ADG</b>	Airplane Design Group
<b>ALCCA</b>	Aircraft Life Cycle Cost Analysis
<b>AR</b>	Wing Aspect Ratio
<b>ASDL</b>	Aerospace Systems Design Laboratory
<b>BAU</b>	Business as Usual
<b>BLP</b>	Berry Levinsohn Pakes
<b>BTS</b>	Bureau of Transportation Statistics
<b>BWB</b>	Blended Wing-Body
<b>CASM</b>	Cost per Available Seat Mile
<b>CC</b>	Contingent Claims
<b>CCP</b>	Conditional Choice Probabilities
<b>COC</b>	Cash Operating Cost
<b>CTOL</b>	Conventional Take-off and Landing
<b>CV</b>	Carrier Based
<b>DBD</b>	Decision-Based Design
<b>DCF</b>	Discounted Cash Flow
<b>DOC</b>	Direct Operating Cost
<b>DOD</b>	Department of Defense
<b>DOE</b>	Design of Experiments
<b>DP</b>	Dynamic Programming
<b>DTA</b>	Decision Tree Analysis
<b>EP</b>	Ericson and Pakes



<b>ERA</b>	Environmentally Responsible Aviation
<b>EU</b>	European Union
<b>FAA</b>	Federal Aviation Administration
<b>FLOPS</b>	Flight Optimization Software
<b>FOC</b>	First-Order Condition
<b>GA</b>	Genetic Algorithm
<b>GDP</b>	Gross Domestic Product
<b>GT</b>	Georgia Tech
<b>ICAO</b>	International Civil Aviation Organization
<b>iid</b>	independently and identically distributed
<b>IO</b>	Industrial Organization
<b>IPPD</b>	Integrated Product/Process Development
<b>IRR</b>	Internal Rate of Return
<b>JSF</b>	Joint Strike Fighter
<b>LBD</b>	Learning by Doing
<b>LCC</b>	Lifecycle Cost
<b>LRMC</b>	Long-Run Marginal Cost
<b>MC</b>	Marginal Cost
<b>MCS</b>	Monte Carlo Simulations
<b>MDO</b>	Multidisciplinary Design Optimization
<b>MPE</b>	Markov Perfect Equilibrium
<b>NASA</b>	National Aeronautics and Space Administration
<b>NE</b>	Nash Equilibrium
<b>NG</b>	Next Generation

<b>NLP</b>	Nonlinear Programming
<b>NPV</b>	Net Present Value
<b>OD</b>	Origin-Destination
<b>OEW</b>	Operating Empty Weight
<b>PED</b>	Price Elasticity of Demand
<b>PIP</b>	Performance Improvement Package
<b>R&amp;D</b>	Research and Development
<b>RASM</b>	Revenue per Available Seat-Mile
<b>RDS</b>	Robust Design Simulation
<b>RDT&amp;E</b>	Research, Development, Testing, and Evaluation
<b>RJ</b>	Regional Jet
<b>ROA</b>	Real Options Analysis
<b>SA</b>	Simulated Annealing
<b>SLP</b>	Sequential Linear Programming
<b>SoS</b>	System-of-Systems
<b>SPE</b>	Subgame Perfect Equilibrium
<b>SQP</b>	Sequential Quadratic Programming
<b>STOVL</b>	Short Take-off and Vertical Landing
<b>TIF</b>	Technology Impact Forecasting
<b>TIM</b>	Technology Impact Matrix
<b>TOGW</b>	Take-off Gross Weight
<b>TR</b>	Wing Taper Ratio
<b>US</b>	United States
<b>VDD</b>	Value-Driven Design

## SUMMARY

Aircraft family design and production is a complicated process that includes numerous decisions across various disciplines, where these decisions should be made in a coordinated manner to maximize the program value. Successful commercial aircraft programs hint that increasing the commonality between different products is not necessarily the goal, but a common and a useful tool for aircraft manufacturers to introduce multiple products to the market with reduced research, development, and production time, uncertainty, and costs. However, in order to make sound and value-adding decisions throughout the family program lifecycle, engineering aspect of the family design problem should be considered concurrently with the manufacturing and marketing aspects.

The large commercial aircraft market, specifically the narrow-body market, consists of unique features that must be captured in order to provide a realistic model. Most importantly, due to high entry costs, there are only a few firms that offer a variety of products sharing common parts to serve different segments. Historically a duopoly, over the last years, new firms have been entering the narrow-body market encouraged by the fast growth of the total market demand. From an entrant's perspective, the evolution of the market must be analyzed for multiple decades before an entry decision is made as any value-oriented firm will try to ensure, even before initiating the R&D investment, some anticipation for a positive balance at the end of a program. These observations extend the market-focused product family design problem, which naturally includes the commonality and commercial value considerations, to also account for segment-level entry/exit options, competitive reactions, as well as endogenous and exogenous uncertainty associated with the firm-specific and market-specific dynamics. The analyses required for such a complex problem are not included in the traditional design methodologies.

To bridge this gap, a competitive product family design methodology is created. At the core of the framework is a multi-product, multi-firm dynamic market simulation featuring

two types of players: the incumbent firms and the new entrants. The main motivation of these players is to maximize the family program value by making economic and financial decisions under uncertainty and strategic competition. The stochastic game in that stage is modeled as a competitive Markov Decision Process in which the players act non-cooperatively and make value-maximizing decisions based on the aforementioned elements. The model utilized in this stage is an Ericson-Pakes class Industrial Organization model which allows the firms to enter/exit at segment level and decide on strategic control variables for the in-production aircraft. It is hypothesized that the combination of an Industrial Organization model with Monte Carlo Simulations will allow the designers to better estimate the expected program value and quantify risk in the early design phase.

In the example case study, an experiment was conducted to test the hypothesis via comparative assessment. It is demonstrated that the standard Net Present Value methods, the benchmark, would lead to different decisions compared to the outcomes of the methodology presented in this thesis. It is also shown that the existing methods fail to quantify the risk which is defined as the probability of the program not breaking even. For certain technology scenarios, it is also demonstrated that the benchmark method could result in opposite signs of perceived returns for the program possibly influencing the top-level decisions.

From a managerial perspective, the capability to estimate the added program value related to a new technology or a certain design change, before the information is clearly revealed, can yield a significant strategic advantage. Within this context, a Value-Driven Design paradigm is well-suited to the aircraft family design problem since increasing the overall market success of the family is the default goal of such family-oriented studies; the program value can work as a single and meaningful representation as a metric for success. The capability of the framework to directly and indirectly handle both exogenous and endogenous uncertainty will enable the top-level decision makers to avoid risky platform designs with insufficient competitive strength for different market scenarios.

# CHAPTER I

## INTRODUCTION

### *1.1 Motivation of Thesis*

Aircraft family design and production is a complicated process that includes numerous decisions across various disciplines, where these decisions should be made in a coordinated manner to maximize the program value. In today's commercial aircraft industry, strong cost competition forces many of the manufacturers to meet the operational demands of airlines via aircraft families with members sharing common parts. Even though the current commercial aircraft market is dominated by families of aircraft instead of independent designs, most family vehicles are known to perform less efficiently compared to their unique design counterparts [88]. Despite these inefficiencies, successful commercial aircraft programs hint that increasing the commonality between different products is not necessarily the goal, but a common, and potentially useful tool for aircraft manufacturers to introduce multiple products to the market with reduced research, development, and production costs. However, in order to make sound and value-adding decisions in the initial phases of the design process, engineering aspect of the family design problem should be considered simultaneously with the manufacturing and marketing aspects. During this complex process, the design engineers act as the liaison in between. When the design problem is extended to include the commonality and commercial value considerations for the entire family program lifecycle, competition, just as endogenous and exogenous uncertainty associated with the firm-specific and market-specific dynamics, becomes an unavoidable reality. The methodology required for such a complex problem may exceed the capabilities and even conflict with some of the existing traditional design philosophy.

The large commercial aircraft market has some unique features some of which are common in both narrow-body and wide-body aircraft segments. First of all, due to high entry costs, there are only a few firms which offer a variety of products in different segments. Also,

the steep learning curve is an important element shaping the competition especially in the first few years after the introduction [103]. These observations occur in a market where it is not exactly clear if these oligopolistic companies are competing in price, or quantity [114]. In addition to these observations, narrow-body market has some of its own unique properties. Historically a duopoly, over the last years new firms have been attempting to enter this market [22]. Any firm that aims to be successful in this market must adjust its strategies in the light of those properties and design the entire product line with market success in my mind.

Sharing the same wing, empennage, cockpit, and fuselage cross-section are some of the most common practices observed in the aircraft families today. This a priori knowledge helps reduce the complexity of the product family design problem from the numerical optimization point of view, but even so, the framework proposed in this thesis targets to quantify market demand, which is still uncertain and depends on some other factors out of the designer's control. That being said, the marketing aspect of the design problem requires analyzing and reacting to the strategic actions of the competitors following the guidelines of the customer requirements. Literature review indicates that such an approach can be enabled by combined usage of theoretical considerations alongside the empirical market attraction models which can simulate the vehicle acquisition practices of airlines and approximate the actual demand of a given vehicle for a given market segment under competitive reactions [143]. Within this framework, the firm strategy on the demand side is assessed concurrently with the supply side which deals with the commonality and manufacturing considerations. In the commercial aircraft industry, in which the economies of scale dominate the cost mechanics, this is a critical step for companies as effects of learning by doing over the program lifetime must be incorporated to the model to make effective and realistic use of benefits. Apart from the manufacturing cost benefits, it is documented that the derivative design from an existing vehicle needs less research and development (R&D) effort making it easier for incumbent companies to expand their product line giving them a significant advantage in the fixed costs [90]. Though from an entrant point of view, the evolution of the market must be analyzed for multiple decades before an entry decision is made.

That is mainly due to the high sunk costs associated with market entry in the industry as any value-maximizer firm will try to ensure, even before initiating the R&D investment, an anticipation for a positive balance at the end of a program. Due to the importance of timing and the change of the market over the years as well as the number of products and firms, literature has shown that the static and deterministic analysis of the commercial aircraft market is insufficient to explain some of the market observations [43].

## **1.2 Objective of Thesis**

This research seeks to identify the main drivers for the design decisions made by the aircraft manufacturers and quantifying their effects on the overall program value for an uncertain future in the presence of competitors. The overall program value, which is used synonymously with the family program value, is the combined value obtained from all of the family members within the market. Shortly, the primary research question of this thesis is as follows:

**Research Question 1:** *For a given oligopolistic market system with inherent uncertainty, how can an aircraft manufacturer evaluate the expected family program value? How can we use this valuation technique to assess program risk of a new design?*

It is possible to break down this complex question into its core elements. Assuming that the identification of the key market dynamics is paramount to achieve market success, one of the initial steps to answer to the fore-mentioned question is to observe and model the current state of the market. Ensuring future success in the market implies the need for taking the dynamics of the market into account. At this point, it may also be necessary to differentiate between the need to model the current industry dynamics and the need to find the sources of the uncertainty. Assuming that the uncertainty exists both at the market and the firm level, they need to be quantified and properly addressed so that it is possible to attempt a tangible answer to the research question. Therefore, the supporting research question becomes:

**Research Question 1.b:** *What are some of the key features of the Large Civil Aircraft (LCA) market?*

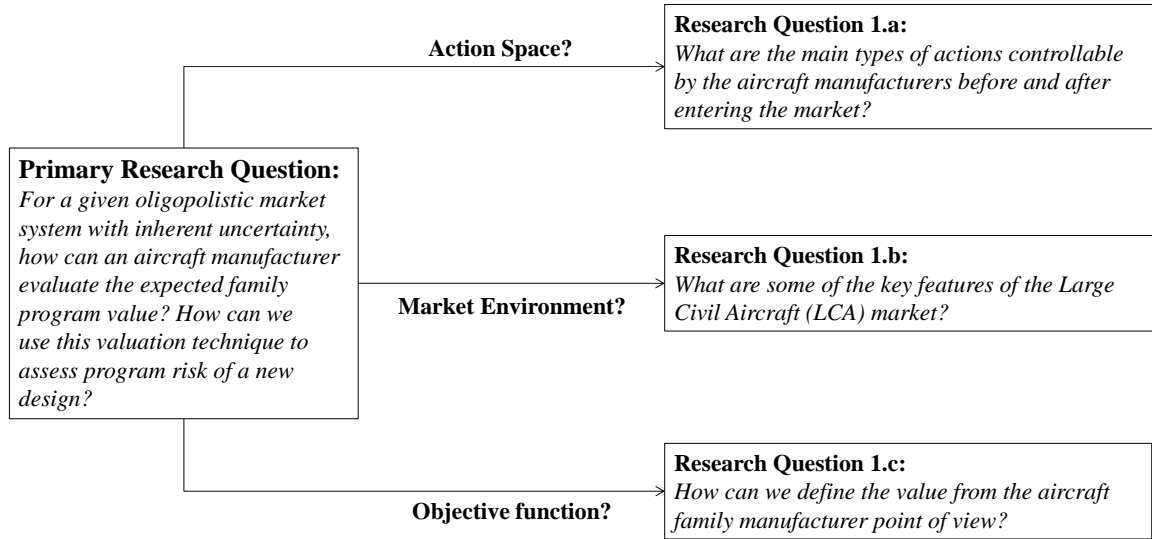


Figure 1: Research Questions

In the primary research question, the implication is that the problem is covered from the aircraft manufacturer point of view. If the main question in mind is to find effective ways to boost the market presence, it is necessary to identify the possible actions or policies that can be controlled by these firms.

**Research Question 1.a:** *What are the main types of actions controllable by the aircraft manufacturers before and after entering the market?*

Finally to encompass these fundamental questions, it is necessary to define the program value:

**Research Question 1.c:** *How can we define the value from the aircraft manufacturer point of view? Once it is defined, what are the enablers to quantify it?*

The following chapters will present the background, existing literature and the proposed framework as an attempt to answer these questions. Figure 1 displays the hierarchy between the primary and supporting research questions.

### 1.3 A Brief Overview of the Experimental Setup

To answer the primary research question, a competitive product family design methodology is proposed within this thesis framework. In the first stage a multi-product, multi-firm dynamic market environment is simulated in which the players are the incumbent aircraft



manufacturers or new entrants. The main motivation of these players is to maximize the family program value by making strategic and rational marketing decisions under uncertainty and competition. The stochastic game in that stage is modeled as a competitive Markov Decision Process (MDP) in which the players act non-cooperatively with the sole purpose of maximizing their own expected rewards. The players within the environment have imperfect information regarding each other's entry/exit decisions. On the other hand, they have the same knowledge about the uncertainty for future exogenous market demand. At each node, a rational decision is made after assessing the state of the market, actions of the competitors, future uncertainty, and some shock associated with internal and external firm dynamics. Cross elasticity of demand is also incorporated to the model in order to demonstrate strategies for smaller firms to possibly capture some of the demand from the other sub-segments the firm is not operating in. We present the subgame in the form of a Bertrand competition of prices. Within this work, the LCA market is divided into narrow-body (single-aisle) and wide-body (twin-aisle) aircraft market segments and we focus on a notional narrow-body market. Classes of different aircraft sizes within each of these segments are further divided into sub-segments.

Around the fore-mentioned first stage is a sizing and synthesis tool that is responsible for evaluating the common design variables among the family members, estimating performance and cost responses for different technology scenarios. This second stage considers the first stage as a black box and provides the vehicle performance receiving program value as an output. For the scope of this thesis, the design decisions will be limited to the technology selection problem. For an infinite time-horizon game, we can obtain the state transition matrices of the industry evolution from the first stage analysis. Then we conduct Monte Carlo Simulations (MCS) to obtain trends of Discounted Cash Flows (DCF) that can help create distributions of Net Present Value (NPV). In this case, MCS will provide useful insights to assess the risk. Since the firms actively react to different stochastic elements, same scenario can result in different market outcomes if the simulation is run multiple times.

This thesis presents an integrated approach to the aircraft family design and valuation problem in a dynamic market. This is mainly because of the fact that this research questions

the main drivers for design decisions made in the early conceptual design of an aircraft family for a scenario where the family is intended to stay in a competitive market with potential entrants over a span of multiple decades. The value-driven approach emphasizes on increasing the program value, instead of more traditional ways of reducing the Take-off Gross Weight (TOGW), fuel burn, etc.. It is believed that the Value-Driven Design (VDD) paradigm is well suited to the aircraft family design problem, since increasing the overall success of the family is the natural goal of such family-oriented studies and the program value can work as a single and meaningful representation as a metric for success. From an executive perspective, the capability to estimate the added program value related to a certain design change or a firm marketing policy before the information is clearly revealed can give a significant strategic advantage. This information can then break down to subject-matter experts and technology developers to make specific trade studies on justifying the R&D effort in means of its impact on the overall program value. The capability of the framework to directly and indirectly handle both exogenous and competitive uncertainty enables the identification of risky designs in the early conceptual design phase. There are existing methodologies that can handle this problem, however when a product family problem is considered, a more comprehensive technique such as the one proposed in this thesis is required. Market-focused design using stand-alone approaches of real options or game theory have certain weaknesses and Industrial Organization models help target a research gap.

The experimental setup at the core of this framework can allow different scenarios to be simulated as well as players' reactions to both incumbent and entrant firms. At each decision epoch, the players can decide on the price of the products for the active segments, to enter a new market segment with a derivative aircraft, or exit an existing non-profitable market segment to prevent further loss. Another important aspect of the aircraft families is the order of introduction of different derivatives. The setup takes this observation into account and can estimate the best course of action in introducing different family members with a certain chronological order. Instead of offering a large variety of products based on the same

platform, it may be better for entrants to offer fewer products, possibly for the popular sub-segments with more specialized platforms. Entry strategies for firms with certain advantages or handicaps, such as lagging or leading technologies, can also be determined, as well as the incumbent firm's reactions to these threats.

#### ***1.4 Document Roadmap***

This thesis document consists of seven chapters with each chapter including the following elements:

- **Chapter I:** Motivation and the overall objectives
- **Chapter II:** Key concepts and fundamental literature
- **Chapter III:** Observations from the industry and formal problem definition
- **Chapter IV:** Specific literature review and overarching hypothesis with the corresponding methodology
- **Chapter V:** Details of the parametric sub-components for the framework
- **Chapter VI:** Experiment to test the hypothesis
- **Chapter VII:** Contributions and potential extensions

## CHAPTER II

### BACKGROUND

The purpose of this chapter is to introduce some of the key elements that are proposed within the thesis framework. Even though this chapter identifies some of the fundamental literature, more specific literature review is presented in Chapter 4. In addition, the readers are informed about some of the advantages and disadvantages of product families as well as some unique characteristics some of which form the motivation of the proposed research.

#### *2.1 Opening Remarks*

In today's competitive market, it has become essential to maximize the commonalities between similar products while trying to provide solutions for the different market segments at the same time. In the last few decades, this problem has received a considerable attention from the community as the customer requirements have become more and more demanding. Historically, some of the product families have been very strong competitors in various markets. By definition, products that share a common platform form the product family [196]. The common platform should have specific features and functions that can satisfy the needs of different customers.

Generally speaking, the design projects are summarized in five categories [194]:

- Variation of an existing product
- Improvement of an existing product
- Development of a new product for a low-volume production run
- Development of a new product for mass production
- One-of-a-kind design

A product family design process may or may not include the baseline design as a low-volume or mass production product. However at all times, the variation and/or improvement of an

existing product is an essential part of the family design activities. Definitions of variation and improvement in this context are not highly distinguishable from each other. Within the context of this classification, it is implied that improvement is a bigger, major change in the design compared to a variation. The term improvement can mean integration of new enabling technologies whereas variation can mean only configurational changes within available resources.

For maintaining an effective competition in the long term, offering a large variety of products is suggested to be a very useful strategy since the customers will be able to choose closer options to their exact demands and wishes [110]. It is also possible to argue that in a market environment in which requirements, main drivers, and even key enablers can change in a very short period of time within the design process, capability to offer multiple solutions for the changing needs can be a significant advantage. It should also be emphasized that as a result of these practices, it is very likely that the manufacturer will be able to increase the market share for the overall product category. In the long run, the whole market demand can also be affected in a positive way benefiting multiple stakeholders. Concentrating on the design of a single product one at a time results in “a failure to embrace commonality, compatibility, standardization, or modularization among different products or product lines” [141]. Common platforms also tend to increase the equipment familiarity for crew and can bring additional benefits that are initially not foreseen [172]. Benefiting from various advantages of mass production efficiency while satisfying individual customer requirements introduces the field called mass customization [165]. For many of the consumer products, success in fast cycle industries depends on faster introduction of new product replacements and model longevity [176]. Based on the example of the Sony Walkman family which is a remarkable design effort supported with continuous innovation in features, capabilities and flexible manufacturing; authors argue that novel and long-lasting architecture creation by Sony which were also fast in replacing the aging designs were the key enablers. Successful design of a product family brings a bigger challenge for designers compared to the design effort of a single product since it has all the difficulties of a traditional point design with the complexity of maintaining the design of multiple products to “increase

commonality across the set of products without compromising their distinctiveness” [183]. Several different methods have been proposed for solving the complicated optimization problem of a family design that have received significant approval from both the academia and the industry; however, the difficulties in the modeling of manufacturing costs, impacts of new technologies and other types of uncertainties make it difficult to realize the true value of the product families for the future while making the decision-making process even more challenging. Therefore, it is quite important for the designer to realize the specifics of the market the product is intended to serve. All of the methodologies proposed for helping the product family design process includes at least one of these following steps [155]:

- Market segmentation
- Creating the product family architecture
- Determining the attributes of the common components defining the product platform
- Choosing the optimal combination and adaptation of components
- Evaluating the effectiveness of the product family in means of cost and performance.

It is also critical to be able to not only use an existing architecture for the creation of a new one but also to be able to use the design knowledge acquired during the creation of the first product [72]. Two of the most significant advantages of such methods are saving time and money by preventing the execution of a very similar but a separate research effort. Preventing unnecessary variety is often recognized as the second common benefit. The ultimate aim of all these practices is to develop more valuable products with less resources and effort [184].

## ***2.2 Domains of Product Family Design***

A comprehensive product family design process incorporates elements of a conventional single product design, but additional complexity arises due to the multi-dimensional nature of family products. One of the modern approaches to forming a product family design framework was introduced as an extension of the existing Georgia Tech (GT) Integrated

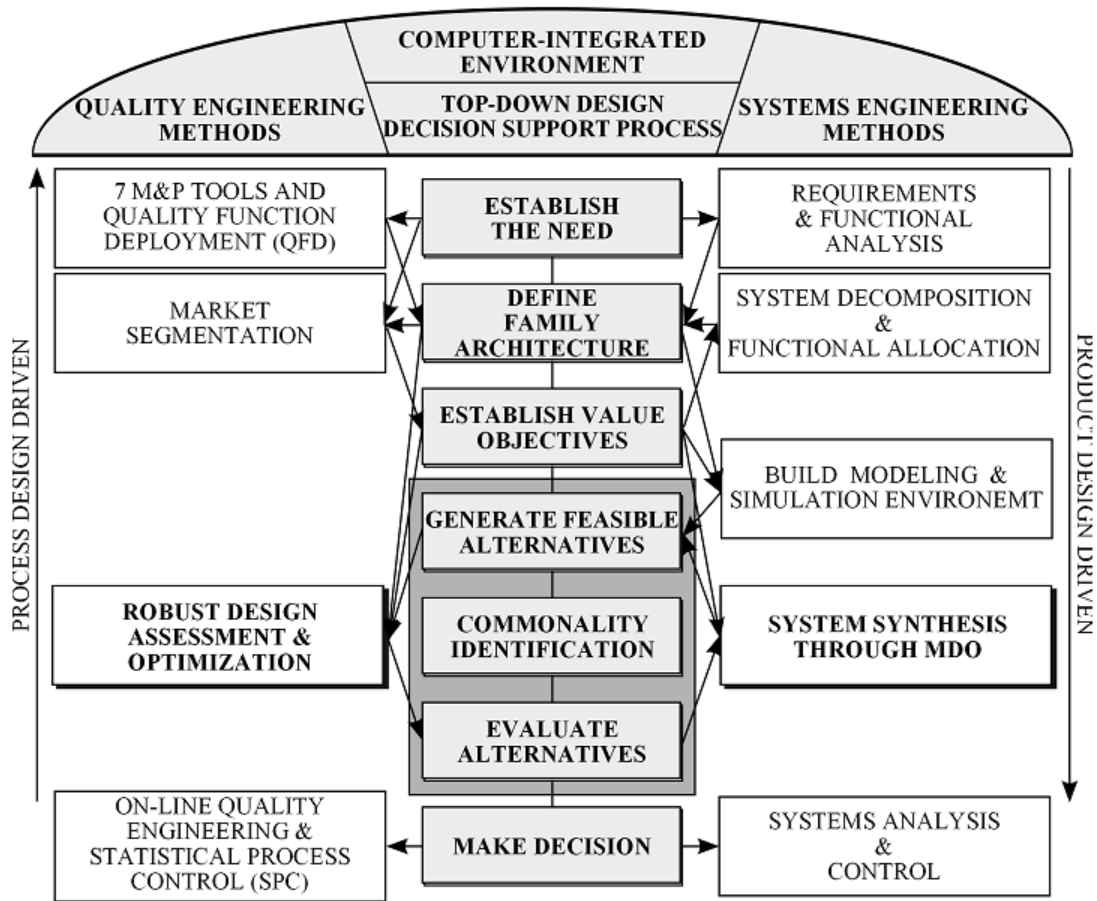


Figure 2: The Product Family Oriented IPPD Methodology [86]

Product/Process Development (IPPD) methodology [86][135]. The need for the suggested product family methodology was aimed at filling the gap in addressing complex System-of-Systems (SoS) where the component commonality is not known. Therefore, the primary focus was the extraction of potential family platform configuration. For the proposed approach in this thesis, this is not the primary goal; however, the modification of the existing GT IPPD methodology is a progressive effort to systematically list the key steps of product family design.

The Product Family oriented IPPD methodology can be summarized in these following steps:

1. **Establish the Need:** This step includes extensive research of customer needs and

market analysis. Analyzing the market dynamics as well as the historical acquisition practices of customers can also be used to identify customer requirements which can also be labeled as “must-be qualities”. There are also “attractive qualities” which provide satisfaction when provided but do not cause dissatisfaction if not achieved [198]. Unlike most of the military systems design projects, competition in the commercial aircraft markets require adaptive strategies and policies to attract more customers. As a result, in a competitive scenario, the concept of “establishing the needs” expands to include not only introducing the products that can operate in the existing environment and stay in line with the mandatory customer requirements and official regulations but also reducing the acquisition cost, improving the operational efficiency etc. to increase customer preference toward a certain product.

2. **Define Family Architectures:** Depending on the context, the word “architecture” may have several different meanings. Apart from the differentiation of the terms “physical architecture” and “functional architecture”, when multiple stakeholders and their own individual motivations are involved; even for the same set of physical products and corresponding functions we may need to define a new perspective. For instance, the architecture for an aircraft family from the manufacturer point of view involves dealing with the commonalities and the technical aspects of the aircraft design etc.. However, from a customer point of view, such as the way airlines utilize these vehicles, very similar products can perhaps be perceived in a different way such as the fleet composition etc.. The family architecture, to better serve the aims of this thesis, is identified as the commonality and the corresponding common design variables between the members.
3. **Establish Value Objectives:** Creating a tangible and non-subjective value objective is important especially for the commonly used optimization procedures. The main concern of an individual product design or a whole product line design is irrelevant; there is usually a need to simplify the complex multi-attribute decision problem to traceable values. This step is needed to emphasize the critical needs and requirements



from the optimization point of view and relevant for achieving acceptable trade-offs between different members of a product family.

4. **Generate Feasible Alternatives:** For creating new and alternative product family designs, a modeling and simulation environment is usually needed. This enables a more extensive exploration compared to what can be done with historical data. The result is the capability to calculate the effect of specific design variables on the high level requirements.
5. **Commonality Identification:** The principal aim of this step is to process the different module spaces and to identify similarities between products. For identifying the commonalities, the observations from the industry are heavily relied on. Chapter 3 is intended to present these findings.
6. **Evaluate Alternatives:** This step is suggested to use high fidelity tools to analyze most likely candidates to narrow down the number of candidates for the final selection step. In a stochastic market environment, the performance of alternatives should perhaps be identified as a probabilistic distribution of outcomes instead of a single number.
7. **Make Decision:** The final goal building on and utilizing the previous steps is to make an informed decision and select the best family design among the possible alternates. The decision-making in this framework is two-fold: The design decisions and the market decisions. As proposed in Chapter 4, the focus of this research is identifying the design decisions that are enablers to more profitable marketing decisions.

The framework introduced in this thesis on the other hand, focuses on all these seven steps except step 5 which has been extensively studied by Freeman [86]. However, this framework doesn't necessarily aim to complement the previous study. Instead a more market-oriented approach is presented. Despite that, these steps are recognized as fundamentals of a rigorous product family design approach.

To provide a comparison to generic product family design approaches, we demonstrate

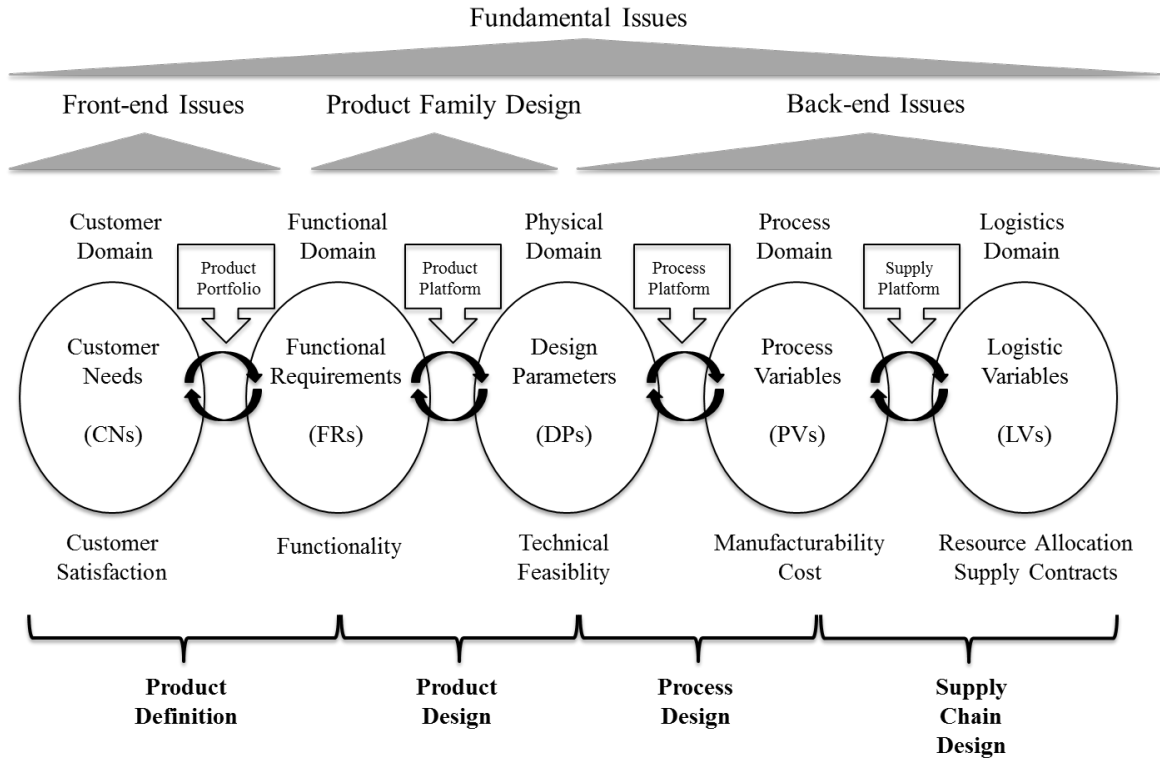


Figure 3: General View of Product Family Design and Development [106]

the segmentation of product family methods as performed by Jiao, Simpson, and Siddique on their review [106]:

In this thesis, the expected contribution to the existing literature of product family design methodologies is made through focusing on the combination of the techniques for identifying on the product family design by addressing the corresponding front-end issues. However, this unique approach extends the front-end issues by taking the approach from a static and deterministic context to a dynamic and uncertain environment which involves Industrial Organization (IO) and usage of empirical models. The back-end issues are only passively considered to come up with a viable business plan as cost is considered. However, endogenous cost dynamics, which are specific to the firm's internal structure, shape the firm policies in the market. Therefore, it is possible to summarize this methodology as a concurrent approach that combines active front-end issues and passive back-end issues with the product platform optimization core. The real challenge in an IO model is to embrace

the existence of uncertainty and the competition. Chapter 3 shows some of the historical examples from the aerospace industry which actually indicates that the LCA market is formed by what can be called as “battle of aircraft families”.

### ***2.3 Classification of the Product Family Design Optimization***

In this section, some of the aspects and extensions of existing product family design optimization techniques will be introduced. In the literature of product family design optimization, different ways of classification exist. Fujita groups product family optimization into three main classes [88]:

- **Class I:** Maximize product performance with respect to product design variables subject to product requirements and component commonality constraints.
- **Class II:** Maximize product performance and component commonality with respect to sharing decision variables subject to product requirements and component commonality constraints.
- **Class III:** Maximize product performance and component commonality with respect to product design variables and sharing decision variables subject to product requirements and component commonality constraints.

Apart from the original classification made by Fujita, an additional third dimension is proposed [116]. This third dimension accounts for restricted versus generalized commonality. At first glance, it may be difficult to distinguish between the platform selection and commonality dimensions. Knowing which components to share and then designing those shared components alongside the unique components would introduce the Class I problem. On the other hand, restricted commonality brings an additional constraint to the platform selection. In the case of restricted commonality, product platform is fully defined including the common design parameters.

A more detailed classification scheme for the product family design problem is also introduced [181]. In this classification, different problem formulation approaches are grouped with the help of the following questions:

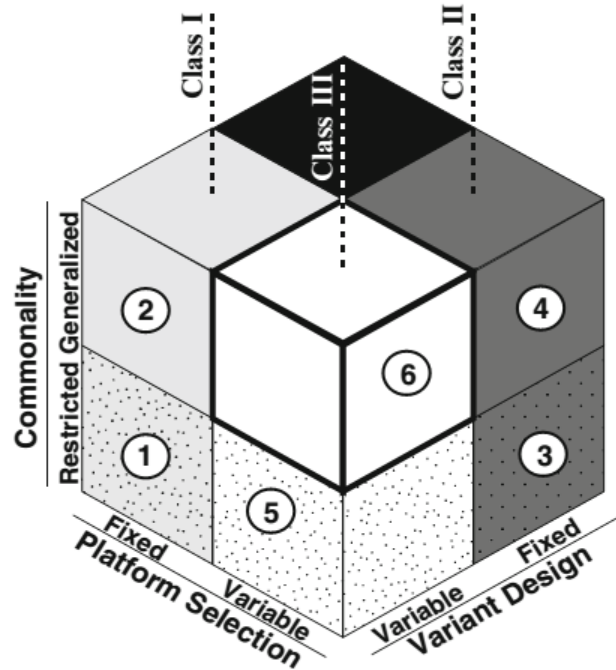


Figure 4: Classification of Product Family Optimization Formulations [88]

1. **Module-based or scale-based family:** Module-based product families are formed by adding, removing or replacing modules from the platform whereas scale-based product families are formed by stretching or shrinking the platform. In the literature, they are also named as configurable and parametric product family designs respectively.
2. **Based on whether the platform is specified a priori:** Class I formulations can help reduce the design space and simplify the optimization process at the risk of converging to a sub-optimal solution.
3. **Single-objective versus multi-objective:** Most of the real-world problems involve simultaneous consideration of different attributes such as maximizing revenue, minimizing risk etc. However, as in any other optimization problem, it is possible to find ways to combine different objectives into one at the expense of certain shortcomings.
4. **Based on whether the manufacturing cost is modeled:** Most of the time firms have to balance the costs and the benefits associated with family-oriented product

design. A comprehensive approach should also involve the back-end of the product development which includes the production processes [183].

5. **Based on whether the market demand is modeled:** Modeling the market demand forms the front-end of a complete product family design. It is a mandatory step for competitive family design for different market systems.
6. **Based on whether the uncertainty is considered:** There are different ways to incorporate uncertainty into product family design. Existing literature mostly deals with uncertainty in the market demand.

The number of stages within the design process is also another way of classifying these optimization approaches:

1. **Single stage:** Optimizing the product platform and family of products simultaneously
2. **Two stage:** Optimize the platform first and then the family members
3. **Multi-stage:** More than two stages in various orders

In the field of product family design, multiple optimization algorithms have been used. However, the most common algorithms are sequential linear programming (SLP), sequential quadratic programming (SQP), nonlinear programming (NLP), genetic algorithm (GA) and simulated annealing (SA). Chapter 4 will involve the classification of the proposed methodology in the light of these classifications as well as grouping some of the specific literature similar to the thesis area. The classifications suggested by Fujita and Simpson are top-level studies that do not necessarily involve the detailed break-down of the existing literature[88, 183]. In the case study of a narrow-body aircraft family, design variables are screened as well as a value metric is defined so that the numerical burden of such design optimization procedures are bypassed.

## ***2.4 Necessity of the Design***

### **2.4.1 Understanding the Market**

In a customer-focused design environment, understanding the specific needs of different customers is crucial. The unique paradigm of a common product platform creation requires attempting to enter multiple market segments simultaneously or in a certain chronological order. Single product designs are more likely to result in program failures compared to product family designs[141]. In such a system it is very likely that such isolated groups will act independently according to their own lifecycle elements. However, the beginning of the life of a new design for both individual designs and groups of multiple similar designs contain the definition of the market. Defining the market and dividing it into multiple segments forms the initiative step of the engineering design process as any failure at this particular stage could fail in the competition even though the final product is a good performer of the intended purposes. The meaning of the “intended purpose” of a commercial aircraft is a satisfactory economic performance of the mission profile by the vehicle while maintaining the regulatory obligations and safety limits.

Marketing for engineering design has two major aspects [160]. The first step, market research, is more important for the conceptual designers at the first glance since it involves identifying the customer needs, product opportunities, and an understanding of the market segments. The second step includes the introduction of the aircraft into the marketplace and continuing customer relations which is excluded within this thesis. For example, spare parts and global customer support network are two very important elements that influence airlines' decisions of aircraft choice as well as creating an obstacle to new players in the LCA market.

This framework focuses on a combination of technology push and market pull. Different technologies are investigated and the added value for each are quantified. The framework can also be considered to assess different scenarios of market pull in a way that the product platform can provide the means to enter different segments. For such markets, it is possible to argue that these two strategies go hand in hand. In simple terms:

- **Market pull:** The instance of a product being developed as a response to an identified market need.
- **Technology push:** The situation where a company has a proprietary technology that can be used to penetrate different market segments [195].

This framework examines the usage of common modules for the later derivatives or scaling the existing parts such as stretching an existing fuselage. Scale-based platforms for penetrating different market niches will be explained in the following section. As an example, Boeing has developed many of the commercial transport aircraft as “series” or “variants” derived from a baseline aircraft. Stretching the aircraft has been a common method of accommodating more passengers or carrying more cargo payload as well as different modifications to increase the flight range [172]. The product family typically addresses a market while specific products or groups of products within the family target niches within that market. The target niche can be a market segment which can be defined as a specific market area where unique customer requirements exist [141]. Market segmentation is an important activity in a customer demand environment which is diverse and varying [186].

#### 2.4.2 Market Segmentation

The market-driven approach to the introduction of a new family of aircraft for the current market should be supported with tangible market analysis. Division of the existing market into multiple segments and identifying the needs and the actual operations will allow to specify the products that can serve in those specific markets. Specification of the design as an initial and essential stage for the single point design process, depending on the situation, can be the most difficult part of the conceptual design. Since one of the main goals of a product family is to introduce multiple products to cover more market segments with less effort. The question succeeding this motivation may be: “What should be the capabilities of my family members?”. This phase, also known as the problem definition or requirements definition can also be summarized as “creating a statement that describes what has to be accomplished to satisfy the needs of the customer” [36]. In this case, the main focus will be on a clear and realistic specification of the mission profile as well as the performance and

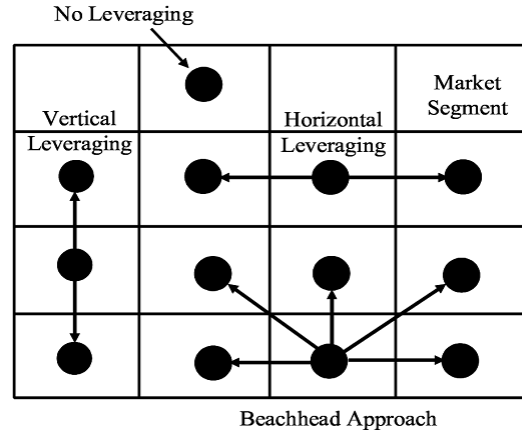


Figure 5: Leveraging Strategies for Product Family Design [66]

geometric constraints imposed on commercial aviation.

Meyer gives an example of a basic market segmentation grid in which the vertical axis represents the cost of the product while the horizontal axis represents different market segments which are not necessarily better or worse than others but essentially represent different product types [141]. Common platform leveraging strategies are classified in three main categories [66] :

- **Vertical leveraging:** Changing the product platform for serving different segments.
- **Horizontal leveraging:** Sharing common platforms across the segments.
- **Beachhead Approach:** The implementation of the initial common platform towards various market segments.

Vertical leveraging can usually be considered as a higher risk and higher return strategy. Common components and technology may still be used and it is not possible to claim the new product is completely independent from the previous ones as occasionally a new product is created simply by removing certain components and functions. However, some components may have certain characteristics that will make scaling, enhancing, or degrading, etc. as difficult as designing that new component from scratch. On the other hand, horizontal leveraging is often seen as a more profitable strategy. This strategy is a way of introducing multiple products across the market while reducing the development costs significantly



although sharing common modules can also result in a series of products sharing common problems. As previously mentioned, one of the main benefits of having a product family is the increase in the production volume for certain components and unforeseeable problems can easily be spread all across the market. In today's market, this alone represents a huge problem since many companies have suffered economically and in terms of perceived company image from problems related to commonality. However, for the scope of this study, such an analysis and assessment will not be possible since risk/reliability analysis is usually not seen as an essential part of the traditional conceptual aircraft design. The beachhead approach is often considered the most difficult and ambitious strategy [66].

Considering three different classes of leveraging strategies, historical examples of aircraft families exhibit different types of characteristics. For a given passenger class e.g. 110-seat class, there is not a high-end or a low-end vehicle; although, the vehicles may perhaps be differentiated by different acquisition and operational costs potentially due to different technology levels. Still, high entry costs shape some of the leveraging strategies similar to horizontal leveraging strategies observed from the industry. Vertical leveraging strategy can be demonstrated in the aircraft families by potentially introducing a brand new wing design to better serve some of the market segments. This will be supported in details by observations in Chapter 3.

### **2.4.3 Market Demand**

Introduction of a flexible baseline vehicle is necessary for profitable module-based enhancements to increase the utilization of the whole product family. Each step will require careful consideration of the alternatives so that a competitive line of products can be selected considering certain noise factors. Analysis of the market demand is also one of the main areas of interest to shape the evolution of a new line of aircraft by giving clues about potentially profitable strategies of attacking various niche markets.

“Market demand” is a term that may have multiple meanings depending on the context. For a certain segment with fixed customer requirements, it may mean the total quantity of products that will be purchased by the customers regardless of the number of manufacturers,

design qualities or pricing. However, in most of the literature, the primary implication is the number of products the manufacturer can sell within the existing market segment based on the actions of the competitors assuming the company can decide on its designs and pricing or quantity policies. Estimating the market demand is a mandatory and crucial link to combine marketing and engineering efforts and forms one of the critical elements of this research.

Overall, manufacturers want to develop and build products that are desirable. This can be a useful enabler to maximize the profit in a competition environment. Once the customer expectations are specified, the manufacturers can work on those metrics to improve the desirability; however, this may not always be a simple and straight-forward task. Volatile market conditions, diverse customer preferences, and the competition among similar products make it a difficult task [107]. There are multiple methods in the literature that attempt to model the complex behaviors of customers in the product acquisition phase and those are detailed in Chapter 4.

Although variety of distinctive methods exist to estimate the market demand for a given product at a given time, those methods are usually implemented for maximizing the margin between the customer-perceived utility and the cost or price of a product [113]. Other metrics that can be used independently or relevantly include the maximization of profit, the market share, or the seller's welfare. Unless supported by detailed cost analysis, these goals may not be achieved in a realistic manner; therefore, detailed modeling of manufacturing cost characteristics is an equally important step for this research.

## ***2.5 Structure of the Design***

### **2.5.1 Commonality**

In a sector like aerospace industry in which the economies of scale are dominant compared to others, commonality is a powerful enabler for reducing the cost of products. The complete and finalized products may not be common among different market segments but the shared components can still give significant advantages to each variant. Therefore, commonality is not necessarily the goal but may be a useful tool in the presence of competition. The

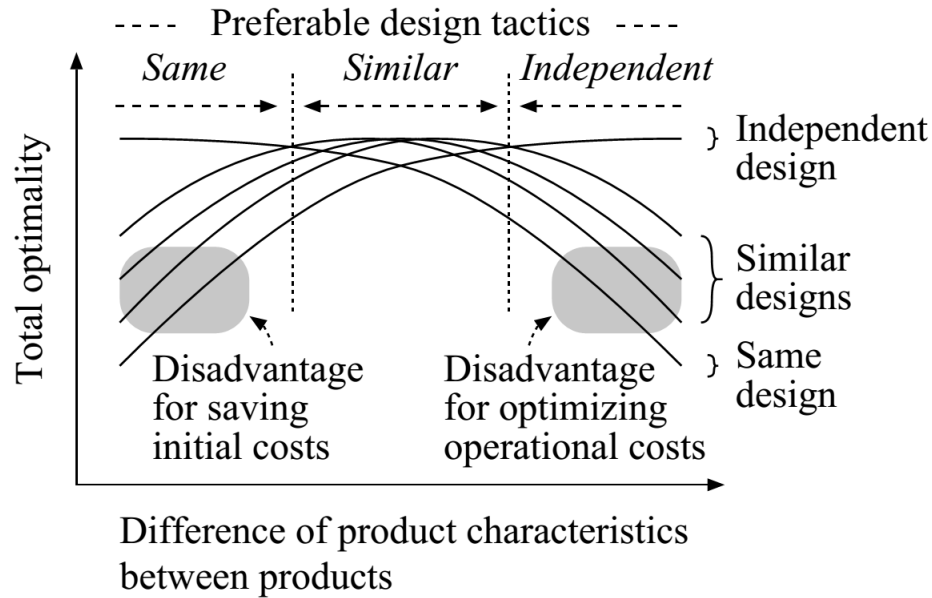


Figure 6: Optimality between Design Tactics [89]

difficulty of designing and introducing product families is mainly a result of the tradeoff between product commonality and distinctiveness. Commonality doesn't only offer reduced production costs but also decreased lead-time and risk during product development [191].

Generally speaking, an increased commonality leads to a higher production efficiency. This often comes at the expense of compromised individual product performance. The technical assessment of commonality must be done in conjunction with the market segmentation and the evaluation of performance metrics. Figure 6 is a representation of how different leveraging strategies target different spectra of customer needs in more "optimal" ways [89]. In this representation, "optimality" is not defined in a quantifiable or objective way and in fact defining the objective function is usually regarded as another topic on its own. The main implication is that if the grouped customer needs differ significantly from each other, this may translate into diverse engineering requirements which in the end may handicap the performance of highly common product lines.

In this thesis framework, commonality is not necessarily forced in the aircraft family design although the term "aircraft family" suggests the usage of common parts and modules. However based on historical examples, commonality is recognized as a very profitable tool

for the primary stakeholders. This is perhaps valid as long as the market study is conducted properly and it is also decided that the customer needs do not differ from each other greatly. Successful examples from the industry include the following:

- **Sony Walkman Family:** Sony utilized common platforms and modular design to accomplish variety. Their incremental innovation strategy allowed them to target different market niches with different models [176].
- **Xerox Copier & Typewriter Family:** Xerox eased the development process between different generations by intentionally increasing the number of modules that could be carried over to the next generations [77].
- **Swatch Swiss Watch Family:** Swatch was able to produce a large variety of Swiss watches by implementing modular design. Most of the models were created by a small selection of modules.[195]
- **Black & Decker Power Tool Family:** Black & Decker produced an entire range of power tool products using standardized components. This allowed the reduction of production cost and lead-time.[127]
- **Boeing Commercial Airplane Family:** Boeing's strategy on commercial airplanes is regarded as "strategic stretching" to accommodate various passenger capacities and flight range. [172]

In Chapter 3, the commercial aircraft family example is going to be detailed with observations from both the narrow-body and the wide-body markets. It is quite trivial to come up with general labels and classifications when the product families as a way of design norm are observed in so many different areas. So, the conclusion is that the commonality should be assessed by critical analysis per each industry. The specific dynamics of how the commonality influences overall market success is assumed to differ even within a certain market depending on the segmentation.

### 2.5.2 Extent of the Conceptual Design

Intelligent design of a product line is one of the methods to add value to a program. In that sense, the scope of this research effort has to be defined with clear boundaries. Therefore, the extent of the design involved in this framework is limited to “conceptual design of a product family”. This phase was originally defined by Asimow as the first stage of seven phases of design as also called “the morphology of the design” [36]. In the light of his work, conceptual design has been identified by “the process in by which the design is initiated, carried to the point of creating a number of possible solutions, and narrowed down to a single best concept” [67]. Not necessarily specific to the aircraft design, this phase usually requires the greatest creativity, involves the most uncertainty, and requires coordination among different entities involved. The pillars of the conceptual design phase are listed as:

- Recognition of a need
- Definition of the problem
- Gathering information
- Developing a design concept
- Choosing between competing concepts

Raymer defines the scope of conceptual design to the minimum of sizing of the aircraft to find the new take-off gross weight (TOGW), fuel weight, wing size, engine thrust etc.[169]. The main topics in question are usually the overall cost, weight, and the related tradeoffs during this iterative process. During this process, a clear understanding of the requirements is necessary to come up with a configuration that can meet the demands. In this context, rough definition of the configuration when completed means the top-level geometric specifications of the aircraft are specified. This is a valid assumption for this framework however, this more traditional approach of solely focusing on minimizing the TOGW is found insufficient by more recent approaches [134].

At this point, it is crucial to recognize that the common phases of product design (conceptual design, preliminary [embodiment] design, detailed design) may in fact have fuzzy

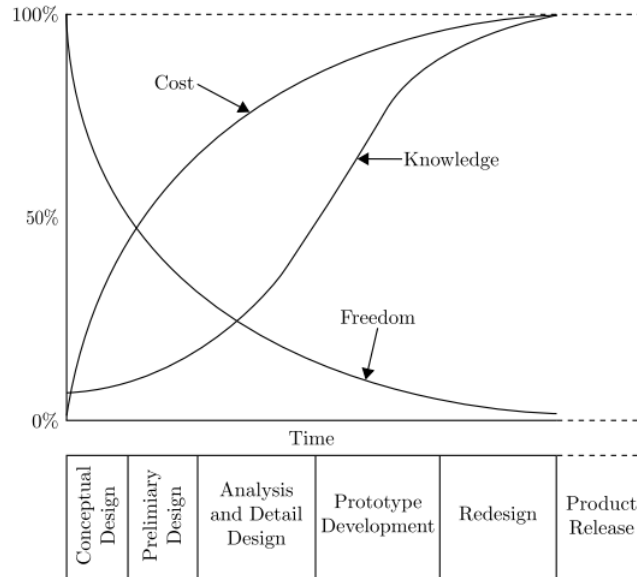


Figure 7: Cost, Knowledge, and Freedom throughout the Design [79]

boundaries. For the optimization approach and the performance models utilized within this framework, certain common and unique design variables are selected. These will be explained in Chapter 4 based on observations from the practices of aircraft manufacturers. Regardless of the number of design variables within the consideration, it is critical to recognize that a modern design approach should always incorporate future uncertainty [194]. Decisions made in the conceptual design process can have a big influence on the overall success of the program. That phase is also the stage where quality can be embedded into the design. However, it is a difficult task to build quality into the design when only limited information is available. Building cost-effective and competitive products requires proper assessment of uncertainty that can be enabled by the selection of right tools and methods. Similar to a single product design, these challenges are also valid for the family design. In fact, designing a product line comes with the increased uncertainty that comes with specifics of each market segment and other commonality related compatibility issues that are not inherent to the common single product design procedures.

## ***2.6 Effectiveness of the Design***

In order to conduct a complete market-focused design study, it is imperative to find ways to measure the effectiveness of the design.

### **2.6.1 Defining the Effectiveness**

The initial problem is perhaps to figure out a method to identify and measure “the effectiveness” for different stakeholders. As a simple example, it is possible to consider a customer buying a car. Some main factors that would be considered are the acquisition cost, future maintenance costs, fuel efficiency etc.. It is also possible to argue that the customer may be interested in something that is not easily identifiable, quantifiable, or observable such as the aesthetics or the appeal of the vehicle to the customer. This, in fact, is another research area. For the car company, the effectiveness of the design starts from the cost analysis and then extends to the demand of their product. An effective design from the car company point of view perhaps has characteristics such as easiness to manufacture, attractiveness to the customer, competitiveness in the market. It is then easy to recognize “the coupling” between the effectiveness of the design from the customer and company perspectives. The car designer should always keep in mind how the product is eventually going to serve the needs of customers which is only a part of the problem. The designer should always make trade-offs between the cost and the performance. This short example so far doesn't possess the specifics of a family design.

In reality, the market will have a variety of customers that can choose not only between different brands but also segments according to their personal interests. Exterior factors such as a steep increase in the fuel prices can suddenly make a fuel-efficient car more appealing whereas the aggressive strategies from the competitors such as discounts and extra features for free can decrease the demand for the product. It has been emphasized previously that the interactions between different market segments and commonality should be assessed simultaneously but in order to measure the effectiveness as an objective, the stakeholder in consideration should be identified as well as an objective metric for the occasion. For this research, the focus is on “the overall family program value” from the

Table 1: Steps in a Product Lifecycle [67]

Premarket Phase	Market Phase
1. Idea Generation	9. Product Introduction
2. Idea Evaluation	10. Market Development
3. Feasibility Analysis	11. Rapid Growth
4. Technical R&D	12. Competitive Market
5. Market R&D	13. Maturity
6. Preliminary Production	14. Decline
7. Market Testing	15. Abandonment
8. Commercial Production	

manufacturer perspective. Program lifecycle for aircraft design projects are described in the next section.

### 2.6.2 Program Lifecycle

In the context of this research, there are two lifecycle considerations. One is the aircraft lifecycle, that of a vehicle, which considers the acquisition, operation, and maintenance of the aircraft as well as the revenue generated by it. That is the perspective of the management of a certain aircraft by airlines. Although this aspect is indirectly included in this study, the main focus here is in the product lifecycle from a designer and manufacturer point of view. Dieter [67] presents a generic program lifecycle grouped into premarket and market phases:

The suggested program lifecycle is intended for the design of a single product. Family programs have substantially different amounts of contributions from different elements of lifecycle cost and the corresponding schedule. First, R&D expenses are higher compared to independent point designs since at least two vehicles are being designed. However, for the example of a two vehicle design, in most cases the expenses are not twice as much as the cost of a single vehicle development [104]. The development effort is also more likely to take longer. The potential benefit of spending more for a longer duration is the possibility of staying in the market for longer and serving a larger market share perhaps resulting in a higher program value. In that sense, the family programs can be considered as “higher risk-higher return” projects compared to individual aircraft programs. Figure 8 represents that approach.



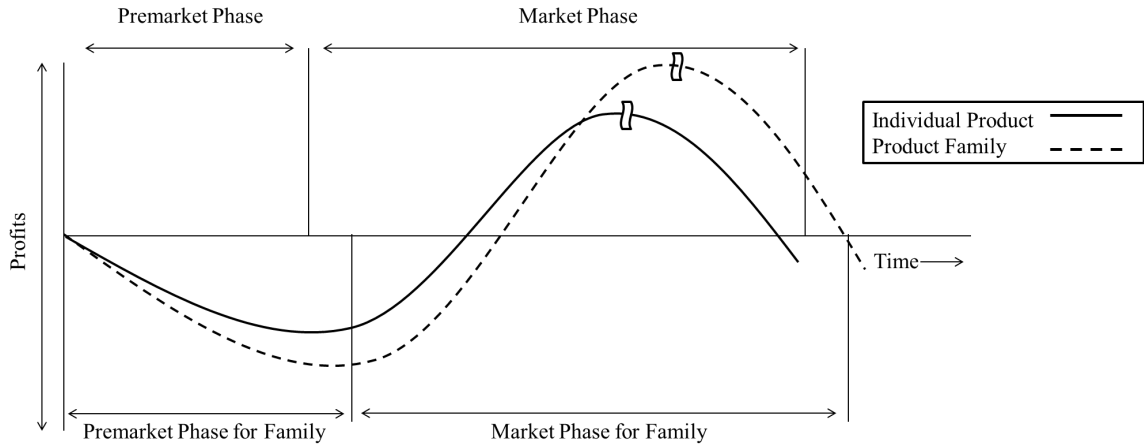


Figure 8: Notional Cash-flow for an Individual Product versus a Product Family

Due to the longer time-span nature of aircraft family programs, the situation requires more careful planning. As the engineers plan later and later into the final stages of the program, the uncertainty may grow to unmanageable magnitudes. Therefore a wide variety of alternatives must be considered and lack of detailed information must be assessed using adequate tools. Although the program success depends heavily on the decisions made in the pre-market phase, proper management and assessment of the competitive environment in the market phase can still make a program more valuable and successful. This is supported by examples in Chapter 3 and techniques for implementing this approach are suggested in Chapter 4.

## 2.7 Value-Driven Design

Value-Driven Design (VDD) is “an improvement to the systems engineering process that employs economics to enable optimization thinking at every level of engineering design” [57]. The VDD approach to large and complex aerospace systems is motivated by the history of cost overruns in both commercial and military aircraft programs which average about 50% in cost and 33% in schedule [37]. It is not possible to add value when the critical and non-negotiable requirements are not met [101]. The remainder of the requirements are flexible but certain attributes may increase the customer value.

The key benefit of the VDD, the ability to formally and repeatably compare different

designs to each other regardless of their environment, has many uses [62]:

1. Ability to conduct trade studies accurately to show which option is better, by how much and why.
2. Ease of optimization via simplifying the objective functions. For example, the project Net Present Value (NPV) can act as a single-objective metric for the optimization routine (i.g. project with the highest NPV is selected). NPV, and similar metrics will be defined in the next section.
3. Better understanding of the design space via obtaining the value surface. This may be a necessary step to help in obtaining robust designs.
4. The value of a change made to the design can be obtained in a quantitative manner. For example, if the baseline system has a value  $V$  and adding a technology increases it or decreases it to  $V'$ , then the value added by the technology implementation is  $V'-V$ .

In this context, different perspectives for “value” should also be defined:

- **Manufacturer perspective:** The value of the overall aircraft family program (Shareholder value)
- **Airline perspective:** The value of a certain vehicle based on the airline operations (Customer value)

The perspective assumed in this research is the manufacturer’s point of view. However there is an obvious linkage between the customer and shareholder value calculations. In fact, forming that linkage is a challenge on its own especially when there are competitive reactions. In practice, every design problem encountered will have its own specifics and it is the responsibility of engineers and managers to identify those specifics and come up with a suitable approach. VDD provides a way of thinking in means of quantifying the result of design changes and firm policies to create value and product differentiation [63]. The ability to compare independent projects using a common value such as monetary values is a huge benefit for top-level decision makers.

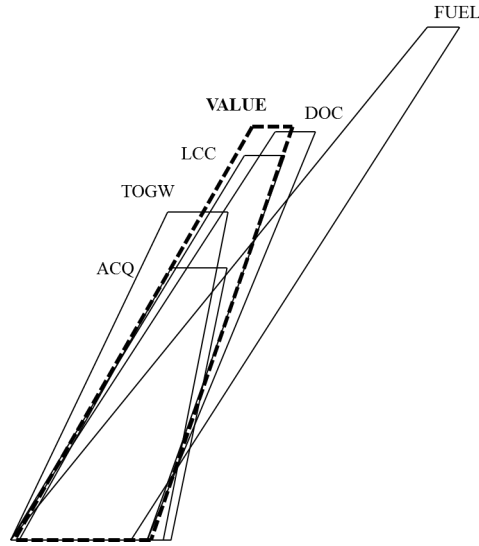


Figure 9: Notional Wing Planform Examples Optimized for Different Parameters

Even though the point of view is fixed to the manufacturer perspective, due to the close relations of value between different entities involved in the process; manufacturers may use different goals of optimization. Following the guidelines of Johnson, the notional demonstration of the effect of using different optimization parameters on the wing planform is expanded by adding the program value [109]. In Figure 9, the effects of fuel burn minimizing, Direct Operating Cost (DOC) minimizing, Lifecycle Cost (LCC) minimizing, TOGW minimizing, and Acquisition Cost (ACQ) minimizing as well as the program value maximizing wing designs are representatively shown. At this point, it is important to highlight the fact that all of these notional wing designs are capable of meeting the customer requirements and the regulations of commercial transport. Therefore, the same missions in question can be performed with varying cost elements and efficiency.

The “value” is notionally demonstrated as a separate objective that may favor certain configurations over others. There is uncertainty involved with all of the designs corresponding to different goals. For example, for the DOC-optimized design, higher fuel prices may result in a bigger aspect ratio wing to increase the fuel efficiency. The uncertainty that would alter the value-driven wing design comes from many different sources, perhaps more than any other designs in the presented example. Since VDD involves revenue management

which in return depends on competitor actions, it is even more complicated. An IO model will be utilized to simulate active managerial policies even after the product is introduced to the market to ensure optimal strategies for maximizing the expected profit with the assumption of “for-profit” firms.

### 2.7.1 Metrics for Value-Driven Design

Today, the commercial program’s success is quantified by the profitability of the products. To do so, the bridge between the three main disciplines should be formed: economics, optimization, and systems engineering. If the value of a project is to be maximized, a meaningful metric for the maximization problem should be chosen. This metric is to be used as an output of an “objective function” in which the inputs are the design attributes and the output is a single value. This overall system objective function is also called a system value model [115]. This selection is a relatively difficult component of any VDD process as each of these metrics have their own advantages, disadvantages, and underlying assumptions. The following are the most common metrics used in value-driven design problems:

- **Net Present Value (NPV):** NPV is calculated as the summation of all the discounted cash flows of a project. The accuracy of this metric depends on the accuracy of the discount rate but it is useful as it provides a consistent comparison metric across different projects.
- **Decision Tree Analysis (DTA):** DTA is the NPV analysis with different future scenarios. The final calculation is made based on the probability of each scenario happening.
- **Internal Rate of Return (IRR):** IRR is defined as the discount rate at which the sum of the discounted cash flows for a project is zero. A major inconsistency with the IRR approach is the possibility of having multiple values for the same project and also the difficulty of interpretation.
- **Payback Period:** The metric for the projected length of time before the initial investment of a project is recovered. This metric doesn’t consider the profile and the

magnitude of the positive cash flow after the initial expenditure is neutralized.

- **Discounted Payback Period:** The payback criterion modified to account for the time value of money.

Now that the final metrics of the candidate project performance are listed, a fundamental step towards calculating any of these metrics requires the ability to first identify and then model the quantifiable attributes of a system. An expansion to this key step is adding the dynamics of a certain environment with multiple options and/or competitive analysis [63]. As an example to these extensions, Briceno uses NPV based competitive analysis to make design choices under uncertainty and competition using principles of game theory [50]. VDD approach has been shown to be well-suited to strategic decision making problems due to the benefits listed. Application of business dynamics on VDD based foundations is not uncommon as Pfaender and Cheung et al. have demonstrated different additions showing how design changes affect the perception of the product value from the customer perspective [164, 57].

## ***2.8 Games and Competition***

A driving force in the commercial aircraft market is the competition. By definition “A game is any activity that involves more than one individual, where the actions of each individual in the game affect others who are also in the game” [95]. Game-theoretic studies can be generalized as the implementation of mathematical models of conflict and cooperation between intelligent and rational decision makers [152]. In this research, the interest is in analyzing the competition. Competition is the state observed when people or entities have utilities, interests, and preferences that conflict with one another. A more specific economics definition of competition is “Rivalry in which every seller tries to get what other sellers are seeking at the same time: sales, profit, and market share by offering the best practicable combination of price, quality, and service” [12]. Among applications of game theory, there are research activities focusing on modeling product family design problem as “a coalition among family members” [148, 147]. That type of research, however, is very sparse.

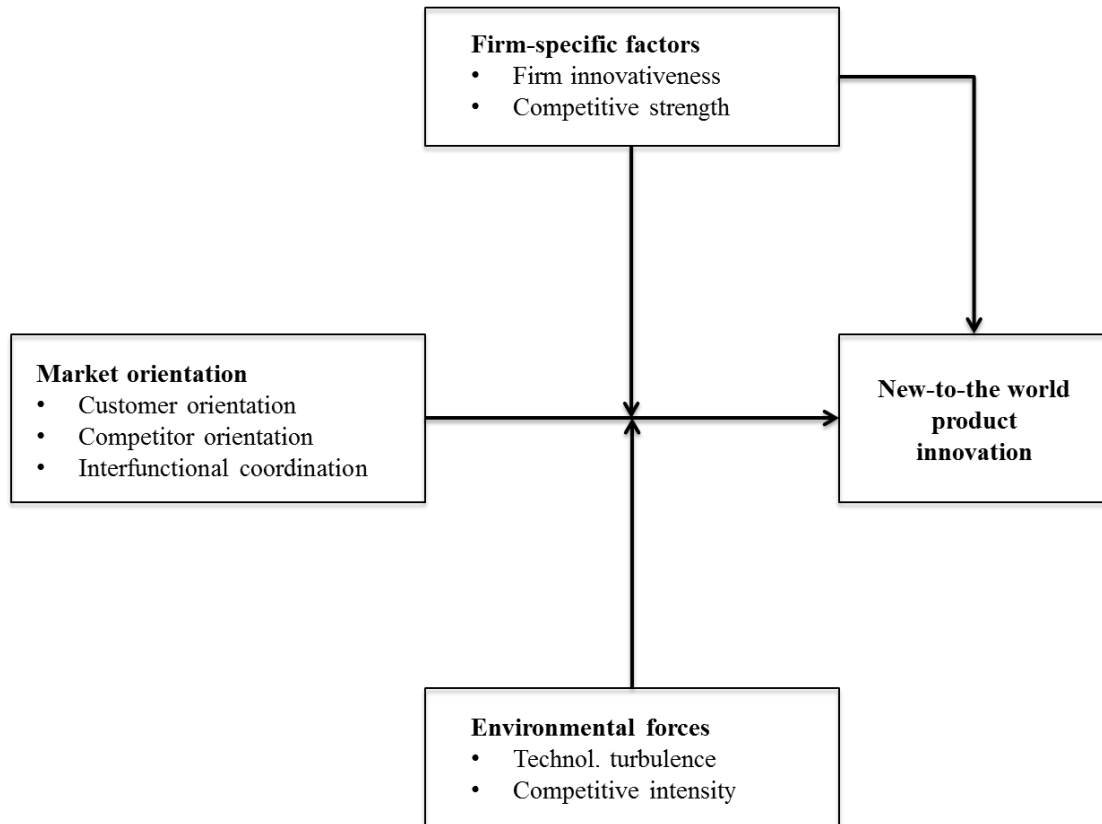


Figure 10: A Conceptual Framework for New-to-the-world Product Innovation [38]

The importance of the proper assessment of competitiveness when introducing a new-to-the world product innovation is crucial and complicated. Innovation is “the adoption of ideas concerning processes or systems that is considered new by the adopting unit” [64]. These main factors that shape the innovation process are proposed by the framework of Augusto and Coelho [38].

New product development is shaped by three main groups of determinants:

- **Market orientation**
- **Firm-specific factors**
- **Environmental forces**

Narver and Slater define the market orientation as an “organizational culture” that defines the necessary behaviors for the creation of superior value for buyers and therefore, superior performance for the business [185]. Customer and competition orientation deals with

collecting the necessary information about the customers and competitors and its implication to the firm. Inter-functional coordination, the third item for the market orientation, is the study of coordination of efforts to create superior value for the buyers based on the fore-mentioned information.

Firm innovativeness is an organization's inclination to "engage in innovative behavior" [140]. Firm innovativeness is mainly the openness of the firm to new ideas, novel approaches and the ability to get stimulated by market needs and challenges. This behavior usually involves risk-taking and needs an active attitude. As a result, the level of innovativeness for a firm determines the company's tendency to use available market information for incremental or innovative products.

Competitive strength is "an indication of the business unit's advantages or position in the market vis-a-vis major competitors and its ability to compete" [51]. It can be achieved in three ways [75]:

- **Differentiation:** Introducing a product of superior quality, higher value and reputation
- **Cost:** Offering products that are cheaper than the competition
- **Agility:** The speed which the company responds to market demands

Apart from these, the firms compete in an environment which doesn't only include the other competitors but also the inherent uncertainty. In fact, the environment as a whole governs the success of a new market entry and their corresponding strategies. In Augusto and Coelho's framework, environment has two additional elements: technological turbulence is "the extent to which the industry is characterized by rapidly changing technologies" and competitive intensity is the extent to which companies face competition [121][40].

In a competition environment, where all the factors should be analyzed simultaneously, focusing on one aspect can lead to very risky or poor decisions. For example, designing a product only focusing on the customer needs without proper assessment of the competitors is a dangerous endeavor. One interesting fact that motivates this research is the assessment of uncertainty that is related to technological turbulence. Long-term strategic planning

in the existence of technological turbulence is already a difficult task but at the same time, requires rapid decision-making. In such a fast-paced decision making environment, coordination between different departments in a firm is also difficult.

For achieving a successful design, the elements of competitive strength are in fact the primary control variables. In this context, the turbulence is the primary noise factor. The firm's ability to anticipate the customer preferences and competitor actions is important and the proper assessment of uncertainty is a necessity. In fact, any study aiming to introduce a competitive product to today's market should incorporate these elements. For these purposes, Porter's definition of competitive strategy is used: "a combination of the goals for which the firm is striving and the policies by which it is seeking to get there" [166]. This definition divides competitive strategy into two critical elements: defining the goal, and identifying the policies.

Chapter 3 is dedicated to defining the thesis problem and explaining the game type proposed in details as a prior step to presenting tools that can help solve the problem. The game is an asymmetric, non-cooperative, non-zero-sum, sequential (dynamic), multi-stage, imperfect information, discrete-time, stochastic game with finite number of players. A brief introduction to dynamic programming, an optimization technique used for solving certain types of dynamic games will also be provided in Section 2.10.

## ***2.9 Strategic Flexibility***

Neumann and Morgenstern define strategy as "sequence of individual decisions geared towards a certain goal [197]. Dynamic and competitive product markets are characterized by high levels of uncertainty about the future value of aircraft programs due to the fact that "products, manufacturing processes, markets, distribution channels and competitive boundaries are in a state of continuous flux" [78]. This makes the selection of a single "best" solution an unrealistic strategic objective [174]. One strong benefit that motivates the introduction of product families is the flexibility to account for changing requirements and the market environment. However, from the flexibility point of view, the way to evaluate the value of the flexibility is through the proper assessment of uncertainty as in fact a



flexible decision is the decision that manages the uncertainty. In this context, the strategic flexibility following the guidelines of Sanchez et al. is considered [175]. Strategic flexibility is the firm's ability to respond to various demands from dynamic and uncertain competitive environments and it is composed of two elements:

1. **Resource flexibility:** Resource flexibility is the ability to use a certain product platform to effectively develop, manufacture, distribute, and market for different range of needs and segments.
2. **Coordination flexibility:** Coordination flexibility is the use of existing resources to adapt to the uncertainty in the competition and the market needs.

This decomposition of strategic flexibility suggests a two-stage approach to the product family design from a managerial point of view. In product families, managers can “coordinate” various decisions such as canceling the entire program, exiting a certain segment, entering a certain segment and quantities to be produced. Managers can also decide on the design of a new platform following the abandonment of the previous one. Due to the stochastic nature of real-life decision making problems, at any decision epoch, managers may also decide to wait for more information to become available. This is rarely observed as especially for aircraft programs, the sunk cost is usually too high to allow a new risky endeavor. The possibilities of coordination flexibility of a manager is bounded by the capabilities of a given platform resource, therefore it can be concluded that these two stages are interdependent and in fact, coordination flexibility can be seen as a part of resource flexibility when the “optimal coordination” is performed by the managers.

At this point, it is important to introduce the term “robustness” and make a clear distinction between robustness and flexibility which are sometimes used interchangeably. Robust design methods such as the Robust Design Simulation (RDS), which was introduced by Mavris et al. propose a new paradigm claiming the traditional design methods “fail to address the presence of uncertainty at numerous levels of the design hierarchy”. The new approach enables robustness at the system level by incorporating uncertainty to multi-disciplinary design optimization (MDO) [139]. The way flexibility differs from robustness

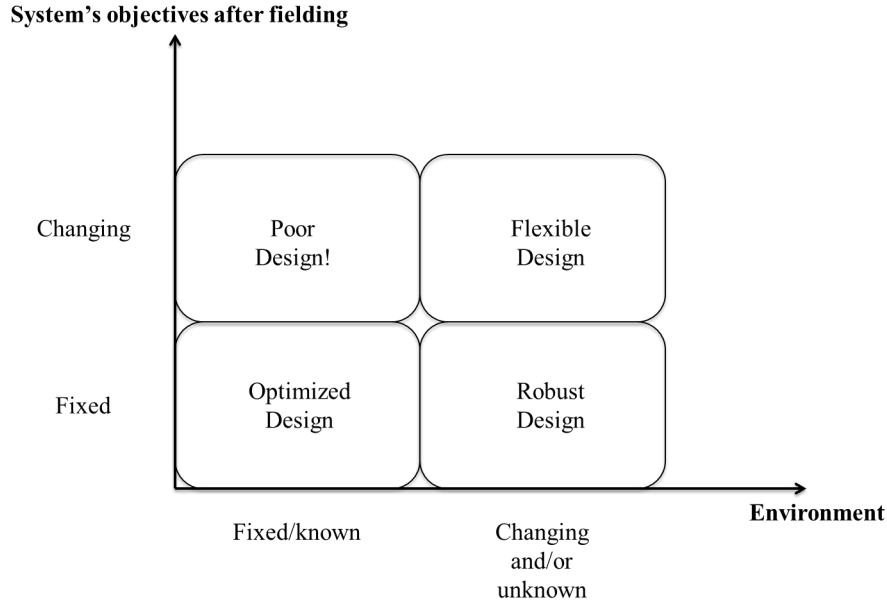


Figure 11: Flexibility and Robustness as a Function of the System Objectives and Environment [173]

as applied to this methodology is on the same page as Saleh et al. [173]. Flexibility is the platform's ability to satisfy changing requirements (entering different market segments) whereas robustness is the platform's ability to satisfy a certain market segment despite changes in the market environment.

Using the wing design example in Section 2.7, now another notional example is introduced to demonstrate ways to incorporate flexibility into the wing design. The notional deterministic program value-driven wing platform design for a single aircraft design is extended to first recognize that the robust design may differ from the deterministic point design as suggested by numerous studies. Based on this, a representative comparison of this VDD for a single small aircraft (1) is extended to a VDD for a single, large aircraft (2), a VDD for small and large aircraft family program with the a priori certain knowledge of both segments will be entered (1+2) and finally a VDD for a flexible program in which the manufacturer is certain to enter the smaller aircraft segment "1" but uncertain about the future and may enter the segment "2" depending on the conditions (1→2). The future conditions may be based on the uncertainty related to the program, market dynamics as

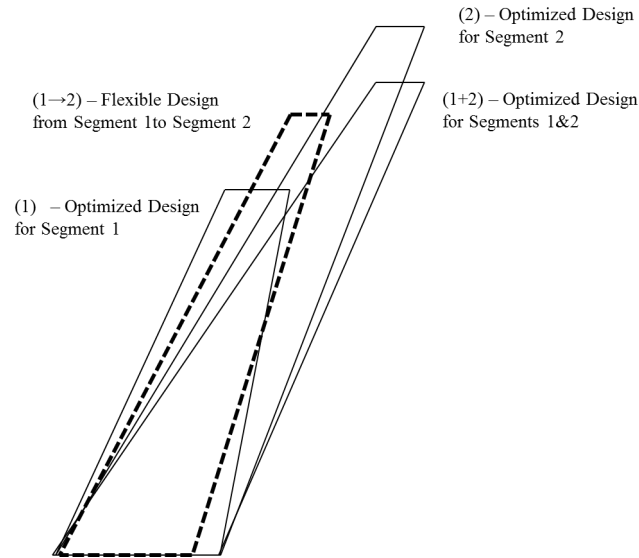


Figure 12: Notional Example of Wing Planforms Optimized for Different Scenarios

well as the actions of the competitors.

The notional example of a flexible product platform presents a paradigm that is similar to the approach of Lim [130]. In Lim's work, the main focus is on enabling future feasibility by trading current sub-optimality. In this thesis, similarly, the value generated only by the baseline vehicle is not of primary importance. This thesis focuses on maximizing the overall family program value by extending the initial platform to developing and introducing new derivatives in the search of a program level optimality.

To sum up, for the next generation product family designs, a myopic policy will fail in the existence of competition and uncertainty [123]. It is not an enhanced decision making tool, but almost a design requirement given the complexity of real-world market environments [177]. This thesis follows a similar paradigm shift, the paradigm shift that resulted in birth of robust design via extension of traditional design, and extends the robust design into a VDD, flexible design paradigm in the presence of competition.

### 2.9.1 Real Options

High-level corporate decisions are made in dynamic environments and managers have the options to consider. These options are used to adapt to changing environment and take advantage of new market opportunities. All of these options to modify projects are called

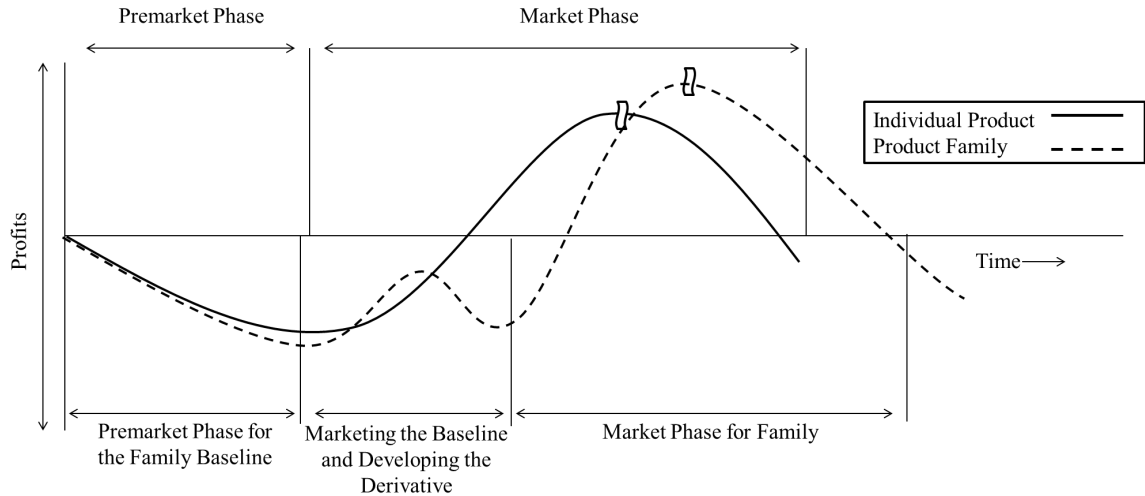


Figure 13: Notional Cash-flow for an Individual Product versus Strategically Introduced Product Family

“real options”. Dixit and Pindyck recognize the analogy between valuing financial options and investments in real assets or real options that consider irreversible expenditures and uncertain future payoffs [68]. Traditional methods based on DCF usually fail in analyzing projects with future uncertainty such as the research problem proposed in this thesis. The option theory is an analytical tool that can be used in such cases to evaluate the projects and help both the design and investment decisions [151].

Observations from the LCA industry suggest that the simultaneous introduction of family members is not common. Instead, a certain version is introduced to form the precursor to other derivatives. Even though the development of a second aircraft heavily based on the first may not be that challenging, this may result in an overlap of marketing and pre-marketing for different designs. Value-maximizing manufacturers will perhaps aim not to delay the introduction of a vehicle that is already designed while designing the derivatives that are cheaper and quicker to develop. This observation is also shown in Figure 13.

Miller and Clarke have implemented Real Options Analysis (ROA) to the R&D process of a new aircraft model [145]. The authors have divided the R&D process into three segments: the preliminary studies, the preliminary design and the product development for which in between these stages, the managers can proceed, wait to proceed or completely

halt the project similar to the approach of Huchzermeier and Loch [100]. This is enabled by the availability of more information as time progresses and the uncertainty for the same time in the future is reduced. These types of decisions must be in complete loop with not only the uncertainty caused by market risk or firm-specific shocks but also the decisions of other players. These factors, when considered together, affect the optimal strategy of a given player and the corresponding timings. Trigeorgis has expressed that the market may force a company to invest early which erodes the flexibility value of a deferred investment strategy [193]. Two well-known approaches for valuing a risky investment using real options theory are:

- **Contingent claims** (CC) with risk neutral valuation
- **Dynamic programming** (DP) using a constant risk adjusted discount rate

For an example scenario combining the flexibility and dynamic programming supported decision making, utilization of commonality can be framed as real options [133]. If a baseline vehicle that hosts the common platform is developed, the manufacturer develops the option to introduce a derivative vehicle for another market segment at a reduced cost and the manufacturer's choice of time. The price of the option is the present value of additional profits the firm would receive if a point design instead of a derivative was produced. From the flexibility point of view, the firm can still develop another point design with no commonality but in such a case, exercise price of the option is higher by the amount of cost savings from commonality.

The next section deals with the fundamentals of stochastic dynamic programming, the technique utilized in this thesis to value an aircraft family program under uncertainty and competition. Insley et al. compare the CC and DP approaches for their applications to pure, stand-alone real options approach [102]. At decision epochs though, managers will immediately make use of the positive value of flexibility by adding the value to the portfolio.

Another work from Aerospace Systems Design Laboratory's (ASDL) research also focuses on adopting flexibility as a useful strategy and to quantify these benefits by comparing

flexible designs to design alternatives which did not have an embedded flexibility [82]. Fernandez found that the flexibility is more valuable when the uncertainty is high, however the author's application of real options to the flexibility in aerospace programs did not involve competitive reactions. One of the examples presented included a winglet option on an airliner.

Adner et al. limit the practical applications of NPV approach to low uncertainty and low irreversibility projects [27]. Low irreversibility, within this context, may mean a project that requires little investment to enter. The same researchers also limit the usage of real options to fixed target market and fixed technical agenda problems. Both of these assumptions are not valid for the problem presented in this thesis. First, the target market is a dynamic market with potential entrants and competition. Second, the technical agenda is not fixed as firms keep the option to design and manufacture a potential derivative. These factors do not completely rule out an application of real options, but clearly indicate that approaches utilizing stand-alone real options techniques are not sufficient to cover all potential strategies.

## ***2.10 Stochastic Dynamic Programming***

Most stochastic games are competitive MDPs where there are two or more controllers or players whose fortunes are coupled either because the probability transitions are coupled or because their rewards are coupled, or both [83]. MDP is defined as a "stochastic sequential decision problem in which the set of actions, the rewards, and the transition probabilities depend only on the current state of the system and the current action selected; the history of the problem has no effect on current decisions" [167]. The underlying assumption is that the players have complete knowledge of these coupling functions but they act non-cooperatively. As described previously, this non-cooperative mindset leads to non-collusive, selfish strategy of maximizing own payoff value. Dynamic stochastic games have always been considered and used to analyze the strategic interactions of forward-looking players in dynamic environments [71]. In addition to this, MDPs are recently more popular among real options applications due to two advantages: they allow endogeneity of firm's decisions

and the unobserved heterogeneity of firms [92].

The design problem in this thesis framework is solved by identifying a certain extension of discrete stochastic dynamic programming as a useful tool to conduct the market simulations. First, a single agent, non-competitive, finite horizon, stochastic dynamic programming is introduced in the guidelines of Bertsekas [45]. The fundamentals are as follows: Time is discrete and indexed by  $t=0,1, \dots, T < \infty$ . The uncertainty is introduced through  $z_t$ , an exogenous random variable that follows a Markov process which follows a transition function  $Q$  and the initial value for the random variable is known  $z_0$ :

$$Q(z', z) = Pr(z_{t+1} \leq z' \mid z_t = z)$$

At the time  $t$ ,  $z_t$  is known. The objective function  $u$  is the expected sum of instantaneous returns discounted by the discount factor  $\beta$ . The return function  $u$  is a continuous and bounded function of the state variable  $x_t$  and the control variable  $c_t$ . The “law of motion” of the state with  $x_0$  known is:

$$x_{t+1} = f(x_t, z_t, c_t)$$

The function  $g_t$  is referred to as decision rule. The action  $c_t$  in each period depends only on the current states through the time-varying function  $g_t(x_t, z_t)$ . Expected discounted present value of a feasible policy  $\pi_T=(g_0, g_1, \dots, g_T)$  from the initial time to the final time  $T$  is:

$$W_T(x_0, z_0, \pi_T) = E_0 \sum_{t=0}^T \beta^t u(x_t, g_t(x_t, z_t))$$

The stochastic dynamic programming problem is to choose a policy  $\pi^*_T$  that maximizes  $W_T$  by solving:

$$\begin{aligned} & \max_{\pi_t} W_T(x_0, z_0, \pi_T) \\ & \text{s.t.} \\ & x_{t+1} = f(x_t, z_t, g_t(x_t, z_t)) \\ & g_t(x_t, z_t) \in C(x_t, z_t) \\ & x_0, z_0, Q(z', z) \text{ given} \end{aligned}$$

Theorem of the Maximum states this dynamic programming problem has a solution using the Feller property [187]. A possible application of stochastic dynamic programming algorithm is the dynamic games which is covered in the following subsection.

### 2.10.1 Dynamic Games

In dynamic games, multiple agents dynamically optimize their policies when their actions affect the welfare of others [146]. For the representation purposes, it is more useful to be consistent with the notation structure of the references used. In a Markov  $m$ -agent game, at each decision epoch the agent  $p$  observes the state of an economic system  $s$  element of  $S$  and takes an action  $x_p$  element  $X$ , earning a reward  $f_p(s, x_p, x_{-p})$ . This time the actions of the other  $m-1$  agents,  $x_{-p}$ , also define the state for the agent  $p$ . This time, state of the economic system is a jointly controlled Markov process by both the exogenous random shock and the previous state of the system as well as the actions of the agents.

The non-cooperative Markov perfect equilibria (MPE) are the equilibria that yield a Nash equilibrium in every proper sub-game. Considering that the agents are aware of the state at time  $t$  and the actions of all other  $m-1$  agents but not the exogenous random shock, a perfect information condition occurs. Following this, MPE is a set of  $m$  policies of state-contingent actions  $x_p^* : S \rightarrow X$ ,  $p=1,2,\dots, m$  such that the policy  $x_p^*$  maximizes the present value of agent  $p$ 's current, expected future rewards when the other agents follow the policies  $x_{-p}^*(\cdot)$  at the discount rate  $\beta$ . Each agent should then solve:

$$\max_{x_p(\cdot)} E_0 \sum_{t=0}^T \beta^t f_p(s_t, x_p(s_t), x_{-p}^*(s_t))$$

where

$$s_{t+1} = g(s_t, x_t, \epsilon_{t+1})$$

The MPE for the  $m$ -agent game is a set of  $m$  number of Bellman equations that should be solved simultaneously:

$$V_p(s) = \max_x \left\{ f_i(s, x, x_{-p}^*(s)) + \beta E_\epsilon V_p(g(s, x, x_{-p}^*(s), \epsilon)) \right\}$$

where  $V_p(s)$  indicates the maximum current, expected future rewards of agent  $p$  that



can be obtained while all the other agents follow their equilibrium strategies  $x_p^*$ . Bellman's equation is needed in order to reduce a problem involving a sequence of decision rules to a sequence of choices for the control variable. This reduces the dynamic problem to a sequence of static problems. Bellman's principle of optimality states: "An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision" [41]. Finite horizon dynamic programming problems are usually solved by a procedure called backward induction. The procedure relies on functional equations used in an iterative fashion in order to calculate the optimal total value function and the corresponding optimal policy.

## ***2.11 Dynamic Stochastic Industrial Organization Models***

### **2.11.1 R&D, Market Entry and Exit**

Since different industries have different characteristics, there is not a single IO model that can capture the key interactions between the firms and the market environment. For this purpose, in Chapter 3, the industry characteristics are observed to characterize certain industry-specific features. For the case considered, based on the assumed description of the "product lifecycle", one of the key elements is the sunk cost related to R&D investment required and the value-oriented firms must ensure a positive cash-flow before making such a risky decision. The managers and top-level decision makers should also consider the uncertainty caused by the time-lag. R&D investments are inherently dynamic and uncertain due to these reasons. This results in a greater option value for a new entrepreneur than it has for an already operating (incumbent) business. Risk increases the option value which pushes some entrepreneurs to high-risk R&D industries such as aerospace industry [47]. Any innovation resulting from the R&D effort changes the structure of the market which can potentially alter the payoffs and perhaps the optimal policies for the remaining players. However, R&D efforts in real life are not really "one-shot decisions" [171].

For dynamic industries that are described by long-run equilibria, market-wide shocks

can significantly affect firm entry and exit decisions. Shifts in consumer preferences, unexpected changes in the manufacturing costs and the introduction of new technologies via new entrants are some of the factors that can affect these decisions. Dunne, Roberts and Samuelson find “substantial and persistent” differences in entry and exit practices. They observe that the entry and exit rates at a given time for a given industry are highly correlated [73]. Caves recognizes the existence of a stochastic market process based on the evidence of many firms facing “infant mortality” due to both system-wide and firm-specific shocks [55]. Similarly, a Booz Allen Hamilton study observes that 35% of all newly introduced products fail despite initially anticipating positive NPV at the time of market entry [48]. Olley and Pakes have also related the entry and exit patterns to the firm characteristics [154]. This clearly defines the need for a comprehensive technique to enable proper decision aid methodology where managers can still make decisions after the product platform is defined and competition and uncertainty is present.

### **2.11.2 The Need for Industrial Organization Models**

Real-world problems require the simultaneous assessment of endogenous and exogenous uncertainty. The three fundamental approaches: NPV, real options analysis, and game theory fail to fully address some of the needs in the industry. Despite this fact, they come with certain advantages and disadvantages [58].

Among these three approaches, Industrial Organization (IO) has benefited from the listed advantages of all three and can be seen as a more complex methodology that combines their strengths. IO is a subset of microeconomics that deals with the structure of industries in the economy and the behavior of firms and individuals in these industries [74]. Unlike most microeconomics approaches though, IO focuses on oligopolies where there are a few firms (but not too many as in competitive markets, or only one as in a monopoly) thus deviating from monopoly and perfect competition [192]. Mostly, it is a game-theoretical approach as it has received most benefits from the developments in game theory. At this point, classification of decision situations is necessary to enhance the understanding of the overall picture [58].

Table 2: Advantages and Disadvantages of Stand-alone Approaches [58]

Approach	Advantages	Disadvantages
Standard NPV	Easy to use, convincing logic, widely used, easy to communicate	Assumes precommitment to a given plan of action, often treating investment as a one-time decision (“invest now or never”), ignores flexibility to adapt to unexpected market developments or strategic interactions
Real Options	Incorporates market uncertainty and managerial flexibility, recognizes that investment decisions can be delayed, staged, or adjusted under certain future contingencies	Typically applied to the valuation of a monopolist or proprietary option, ignores (endogenous) competitive interactions
Game Theory	Incorporates competitive reactions endogenously, considers different player payoffs	Typically disregards market uncertainty involving stochastic variables

Table 3: Classifications of Decision-Making Techniques under Consideration [58]

		Decision Theory (no strategic interaction)	Game Theory (strategic interaction)
Static		Net Present Value Discounted Cash Flow	Static Industrial Organization
Dynamic	Deterministic	Resource extraction Forest economics	Dynamic Industrial Organization
	Stochastic	Real Options Analysis	<b>Option games</b> <b>Dynamic Stochastic IO</b>

Brennan and Trigeorgis distinguish static, dynamic, and real-options vs. game-theoretic valuation models [49]. In static models, the stream of decisions is specified with no managerial flexibility. In dynamic models, projects can be actively managed to adopt to an exogenous uncertainty. This can be done via decision-tree analysis, dynamic programming, and ROA models that incorporate strategic interactions with dynamic and stochastic elements. In real-options game-theoretic models, firms condition their decisions not only on the resolution of exogenous uncertainties but also on the actions of competitors. Therefore, the future value is an outcome of a game including multiple players and the market environment.

In this thesis, dynamic and stochastic IO models are used. The following chapters will present the observations from the industry leading to the justification for this choice.

It is hypothesized that certain characteristics of such markets can be better modeled and represented with such techniques at the expense of additional algorithmic and computational complexities.

## CHAPTER III

### INDUSTRY CHARACTERISTICS AND PROBLEM FORMULATION

The proposed research framework is motivated by some of the key and unique aspects of the commercial aircraft market, therefore it is crucial to identify these properties as a precursor. In the first section of this chapter, the observed industry characteristics are identified along with some aircraft family examples. Examples include a military case (Joint Strike Fighter) as well as a commercial case (Boeing 737). This thesis focuses on the commercial aircraft families only, so it is necessary to differentiate between the dynamics of commercial programs and military programs. This differentiation will also enable potential extensions to the framework to account for military applications. Observations indicate that, within the commercial aircraft market, the dynamics in wide-body market and narrow-body markets exhibit different properties. Therefore, it is felt necessary to distinguish between them. Later on, focusing on the narrow-body market, a further discussion on the possible market entry and exit scenarios is made, however, most of these scenarios need serious accounting of uncertainty for the whole program lifecycle. Thus, the emphasis will be on how to collect uncertainty data, quantify it, and use it for value-driven designs. The final Section 3.8, “Formal Problem Formulation”, then converts these “real-life” observations into a design problem. Chapter 4 builds on these essentials to suggest a solution framework.

#### *3.1 LCA Industry Characteristics*

For many years, commercial aircraft have been one of the main exports of United States (US). Only in 2012, the aerospace industry contributed \$118.5 billion in export sales to the US economy with a net balance of \$70.5 billion which is the largest trade surplus of any manufacturing industry. This is achieved by the high 64.3 percent export rate of the American aerospace production. Also on a global perspective, considering the total amount of annual sales, it is straightforward to assume it has been an important economic element for both European Union (EU) and US economies. This industry is usually identified as a

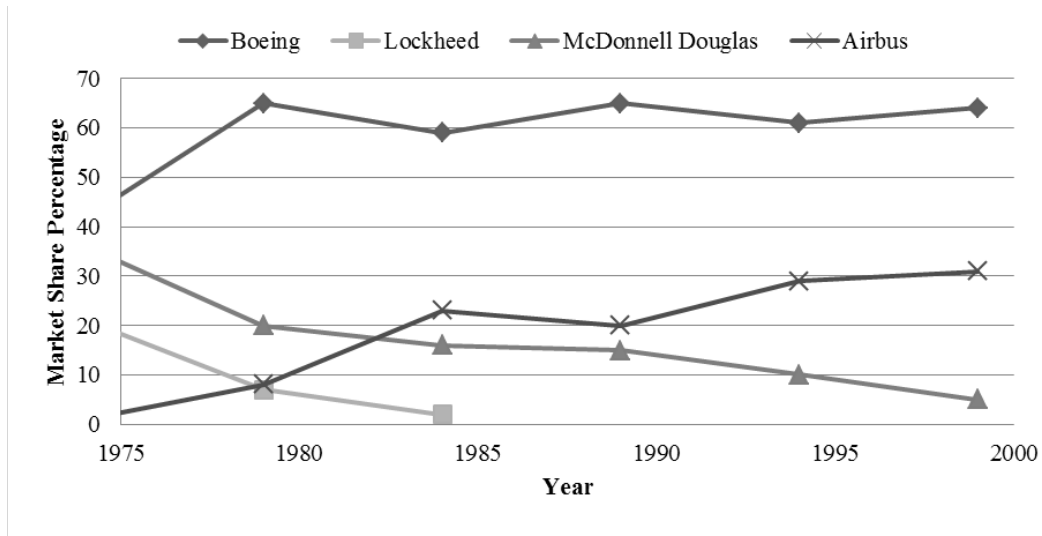


Figure 14: World Market Share of LCA by Value of Deliveries 1974 to 1999 [22]

“strategic” industry, meaning it is critical for the welfare of a nation as well as a source of national pride as an indicator of technological superiority. This argument can be supported by the fact that 500,000 people are employed in aerospace-related scientific and technical jobs across the US and more than 700,000 people are supported in related fields. For the next 20 years, the rough estimates indicate that the number of large commercial airplanes will increase by 3.5% annually for a total of 34,000 at \$4.5 trillion [25].

Commercial aircraft market has constantly gone through changes which are usually shaped by the merger activity. Many of these merger activities have been triggered when the future viability of the weaker firm is debatable. Regardless of the reason, such merger activity has led to a market structure with high concentration. High concentration is not only caused by these activities as the need for large capital investments, leading technical capabilities, and an ability to serve the customers worldwide can be listed as additional factors [52]. The additional difficulty to enter the market due to the size of required capital investments will be detailed in Section 3.4. The Figure 14 shows the merger activity prior to 2000 [22].

The last decade in the commercial aircraft industry has exhibited some duopoly properties with two main players: The Boeing Company of US and the Airbus Industrie of EU. This was mainly a result of the merging of Boeing with McDonnell Douglas Corporation in

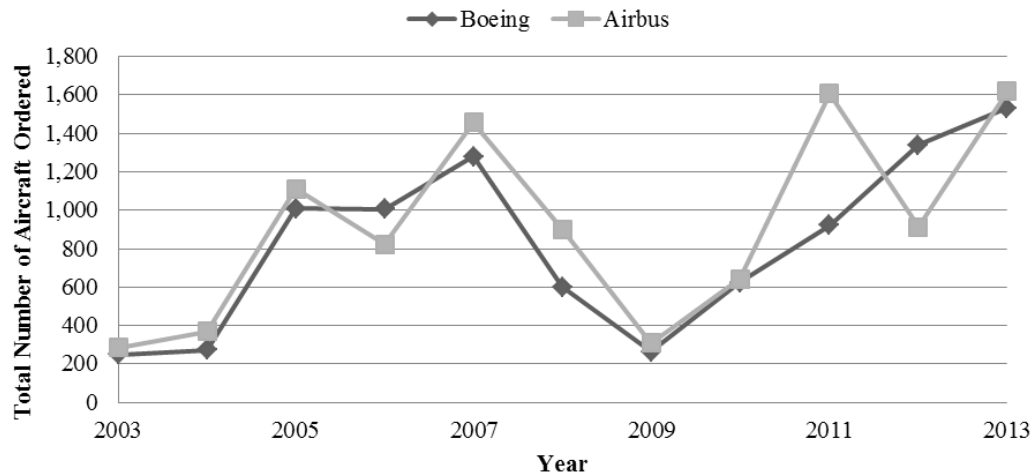


Figure 15: Number of Aircraft Ordered from Airbus and Boeing from 2003 to 2013 [20]

1997 leaving the Western airliners with two aircraft manufacturers. The data presented in Figure 15 clearly shows that these two players have enjoyed very even market shares starting around the year 2000. This data, even on its own can indicate some fierce competition between the duopolists.

Competition within the commercial aircraft industry's unusual structure motivated by its strategic importance has usually triggered governmental trade policies to be implemented on this industry. For example, Airbus-Boeing rivalry has caused trade disputes between US and EU [103]. 1992 US-EU agreement on the trade of civil aircraft has limited the government subsidies which as a result increased the aircraft prices by about 3.7%. Airbus has constantly penetrated into Boeing's market space since it began production in 1970s with substantial financial assistance from European governments.

The policymakers have recently been discussing if US can sustain its powerful position in this fast-growing industry. The narrow-body market has been threatened by possible entries of numerous foreign manufacturers as early as 2017. This is a critical market segment that encompasses about half of all commercial aircraft revenues and more than 60% of commercial aircraft deliveries. Many agree that the long-standing duopoly of Boeing and Airbus is over especially in the narrow-body market [15]. Section 3.6 is dedicated to the observations made on potential entrants.

Overall, the observations from the LCA industry is inconsistent with what the static analysis would suggest. Benkard specifically notes the common occurrence of pricing products below the level of static Marginal Cost (MC) especially after the introduction of a new aircraft [43]. The justification is based on the analysis of detailed cost and price data for Lockheed L-1011. Benkard also uses detailed cost data to introduce an organizational learning and forgetting model, which is used for better explaining the fore-mentioned industry dynamics [42]. Learning curves exist in many industries [35]. Aerospace industry and aircraft production is one of the first documented examples [202].

**Observation 1:** *Aircraft production is the first published case of Learning by Doing (LBD) also known as the learning curve. Economies of scale are enormous relative to small market demand. Recurring costs are reduced through utilization of similar parts across different vehicles.*

Learning curve effects can also ease the predatory pricing. Predation is a set of actions which are unprofitable for the firm that executes them but they potentially contribute to a competitor's exit [156]. Cabrat and Riordan demonstrate how learning curve effects create equilibrium incentives for predatory pricing [53]. They also present that the high industry concentration and aggressive competition in LCA industry are partially caused by steep learning curves. Seitz et al. have found out that out of 22 commercial airplanes developed, only Boeing 707, Boeing 727, and the DC-8 have been profitable [178]. This is a valuable information as on many occasions, aircraft manufacturers try to keep this sort of data confidential.

**Observation 2:** *Static models fail to represent some of the observations in the LCA industry.*

### **3.2 Examples of Existing Aircraft Families**

In this section, some of the observations from two aircraft families will be presented: Joint Strike Fighter and Boeing 737.



### 3.2.1 Joint Strike Fighter (JSF)

The motivation to initiate the Joint Strike Fighter (JSF) program was simple: In June 2000, Defense Secretary William Cohen wrote a letter to Congress stating:

*The Joint Strike Fighter (JSF) program is critically important to the modernization of United States conventional forces and is the cornerstone of tactical aircraft modernization. It will replace 1,763 Air Force, 480 Navy, and 609 Marine Corps aircraft; 2,852 aircraft in total. The JSF's stealth, advanced avionics, and ability to carry a full array of modern precision munitions will make it much more capable than the legacy aircraft it replaces when operating under challenging circumstances against modern air defenses. It is also critical to the modernization of our ally forces for coalition welfare.*

The primary selling point of the idea has been serving diverse needs of the Air Force, Navy and Marine Corps with different types of aircraft sharing commonality to reduce the unit cost. The three planned versions of JSF had the following requirements:

- **Air Force CTOL Version (F-35A):** A conventional take off and landing (CTOL) multi-role aircraft to replace the F-16 and A-10 and to complement the F-22
- **Marine Corps STOVL Version (F-35B):** A short take off and vertical landing (STOVL) aircraft to replace the AV-8B and the F/A-18
- **Navy Carrier-Suitable Version (F-35C):** A carrier based (CV), first day of the war, survivable strike fighter to complement the F/A-18E/F

The initial statement by the Air Force emphasized on the commonality and advanced technologies to meet the cost and performance requirements:

*The F-35 program will develop and deploy a family of highly capable, affordable, fifth generation strike fighter aircraft to meet the operational needs of the Air Force, Navy, Marine Corps, and Allies with optimum commonality to minimize lifecycle costs. The F-35 was designed from the bottom-up to be our premier surface-to-air missile killer and is uniquely equipped for this mission with cutting edge processing power, synthetic aperture radar integration techniques, and advanced target recognition. The F-35 also provides "leap ahead" capabilities in its resistance to jamming, maintainability, and logistic support[157].*

The Department of the Navy statement similarly stated:

*The commonality designed into the joint F-35 program will minimize acquisition and operating costs of Navy and Marine Corps tactical aircraft, and allow enhanced interoperability with our sister Service, the United States Air Force, and the eight partner nations participating in the development of this aircraft. This aircraft will give combatant commanders greater flexibility across the range of military operations. A true fifth generation aircraft, the F-35 will enhance precision strike capability through unprecedented stealth, range, sensor fusion, improved radar performance, combat identification and electronic attack capabilities compared to legacy platforms. It will also add sophisticated electronic warfare capabilities, as compared to the legacy platforms it will replace, and will tie together disparate units scattered across the battlefield, in real time[157].*

The program presents a clear example of an aerospace program that attempts to utilize the commonality for various benefits. Different branches of the military, as well as allied nations, were included into the program to eventually reduce the unit costs through increasing the production volume. With certain tradeoffs between the performance and cost, a common ground was found between different customers with the overall aim of maturing advanced technologies as well as components and production processes.

Most of the avionics, the canopy, and radar are common in all three variants while the fundamental differences are caused by different modes of take off. As an example, the internal structure of the naval version is stronger to withstand the high stresses of catapult-assisted carrier launches and tail-hook arrested carrier landings. The marine version has a lift fan which increases the empty weight and reduces the fuel capacity.

**Observation 3:** *Creating a common platform to satisfy a diverse set of customer requirements may result in reduced program value.*

Some of the difficulties faced in developing the JSF can imply that the additional family design challenges can always be faced due to diverse set of customer requirements. This may be supported by the fact that the program already resulted in a 26% cost increase, as well as a 5 year delay from the baseline established in 2007. The average unit price has almost doubled and the lifecycle cost is expected to be much higher than initial expectations[190].

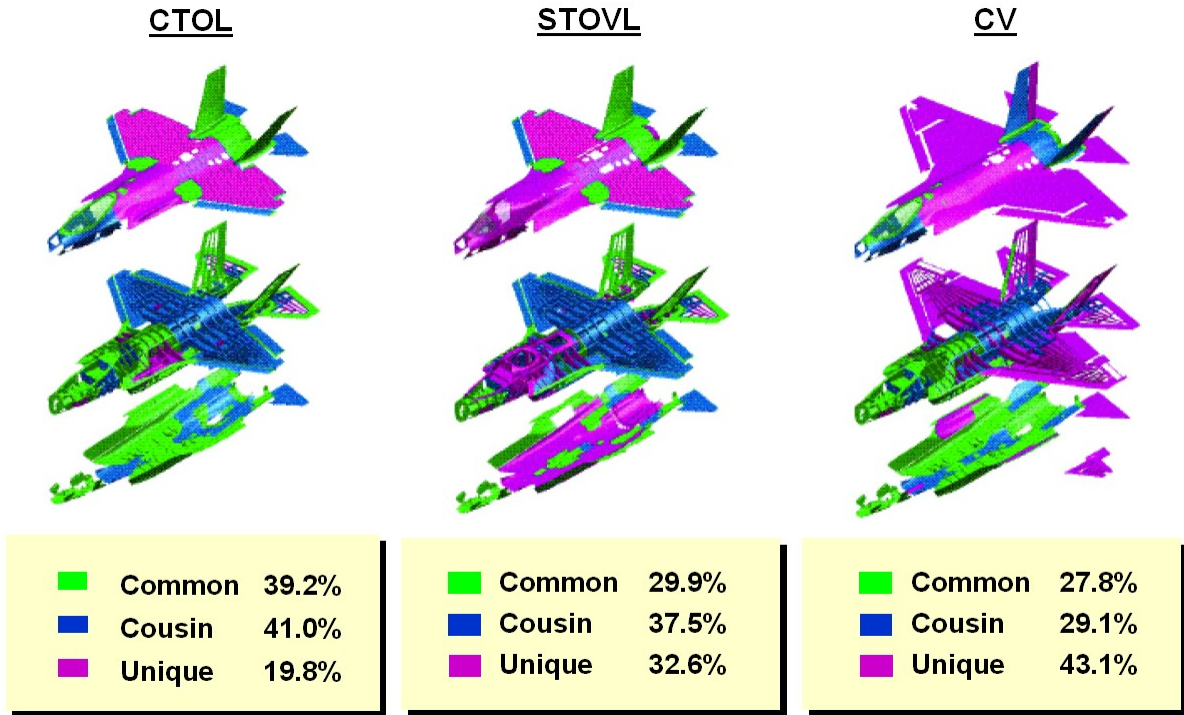


Figure 16: Commonality among Joint Strike Fighter (JSF) Variants [14]

Apart from the increased cost, and possibly additional cost caused by the delay of delivery to the partners, performance problems are also experienced throughout the variants.

**Observation 4:** *Managers of aircraft family programs can still actively be involved and make value-adding decisions even after the design is fixed. For different programs, there are different means to reach that goal.*

The JSF program is a difficult, and risky project, not only due to the fact that diverse needs are satisfied by a common platform, but also due to the integration of advanced technologies. Therefore, it is not straightforward and clear to attribute the problems experienced in the development program to the strategy of using a common platform for such different needs. Various aerospace programs throughout the history have shown that the difficulties, and the risk associated can come from all different sources. However, Department of Defense's (DOD) strategy of decoupling F-35B tests from F-35A and F-35C tests to prevent a complete program slowdown may suggest that the problems related to the JSF program may partially be related to satisfying the demanding needs of Marine Corps

as F-35B has been under-performing in the flight tests. The JSF program can also be an example of the necessity of direct involvement of managers throughout the development cycle.

### 3.2.2 Boeing 737 Families

Before examining the Boeing Corporation's strategy on the 737 family, it is critical to classify different types and levels of commonality observed across different vehicles. For the case of commercial aircraft, commonality can be observed in different ways. In Figure 17, different levels of commonalities between the products of the same company are shown. It is possible to observe:

- **Commonality between families** (e.g. similar flight deck structure between B737NG, B767-400ER and B777)
- **Commonality across generations of families** (e.g. Boeing relies heavily on B737NG while designing on the re-engined B737MAX family)
- **Commonality within the family** (e.g. B737-600, B737-700, B737-800 and B737-900ER shares the same wing as well as many other common parts)
- **Commonality between different versions of the same model** (e.g. B737-700ER has an extra fuel tank, B737-700C is the convertible version in which the seats can be removed to carry cargo instead, B737-700W is the version with winglets and B737-700BBJ is the business jet version)

Within this context, the main intent is to emphasize the vehicle commonality from an engineering perspective. On the other hand, the term “fleet commonality” is also popular among airlines and other stakeholders implying the operational ease of switching between different aircraft due to shared platforms. Utilizing a family of aircraft sharing common platforms makes the operations easier for airlines thanks to the factors such as simplified crew scheduling and ground operations. In the vehicle acquisition practices observed today, this is one of the primary factors. One example is Southwest Airlines preferring Boeing B737MAX over Airbus A320neo (New Engine Option). The chief operating officer of Southwest stated

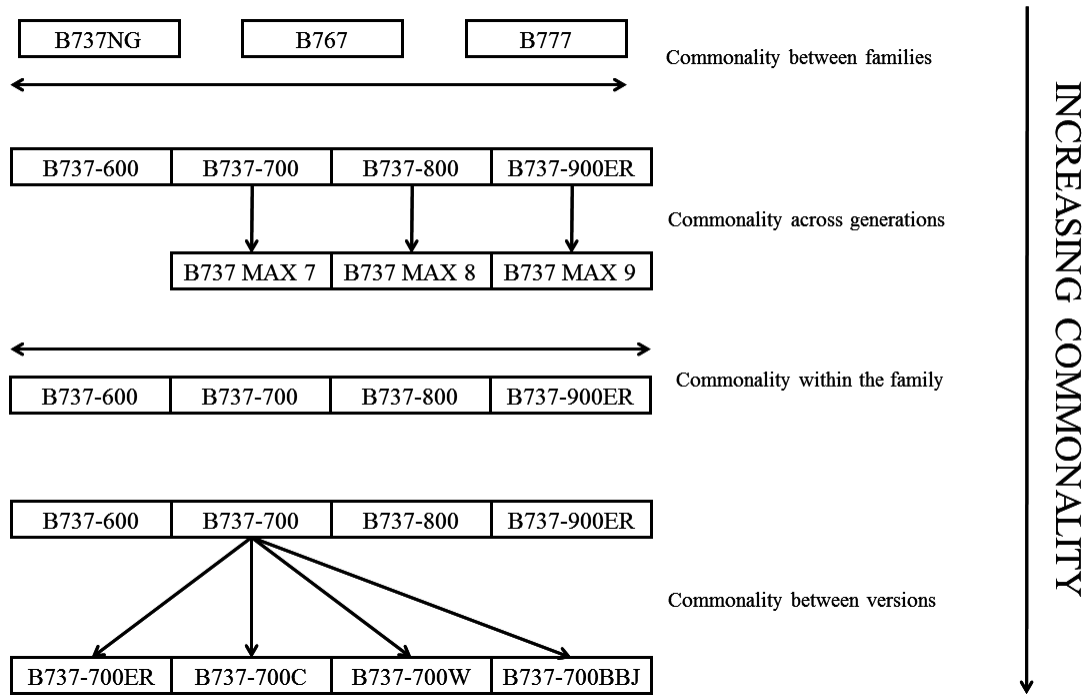


Figure 17: Different Levels of Commonality

that “Choice of the B737MAX guarantees to Southwest Airlines a single-fleet type well into the next decade with all the operational benefits associated with training and schedule recovery and our maintenance programs.” referring to the Southwest fleet composed entirely of Boeing aircraft and primarily of B737-700 [17]. From an engineering point of view, the focus is on parts-based and physical architecture commonalities and specifically following the classification of different types of commonalities observed in the commercial aircraft industry, the primary focus on this section will be on commonality within the family using the Boeing 737 families as an example based on its success.

The best-selling commercial airliner since its introduction in 1968, 737 is arguably one of the most successful commercial aircraft program in the history of aviation. The Boeing 737 series is composed of four generations: the Original series, the Classic series, the Next Generation (NG) series and the MAX series which is planned to be introduced in 2017. MAX series will replace 737-700, 737-800 and 737-900 with MAX 7, MAX 8 and MAX 9 respectively. Boeing has followed a similar strategy in all these generations utilizing the

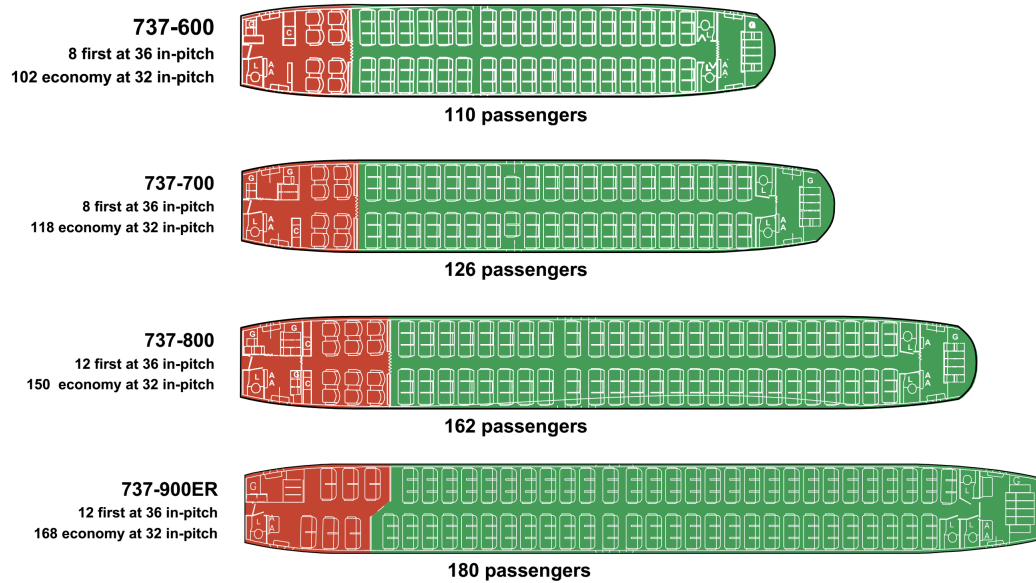


Figure 18: The Seating Chart for Economy Configuration for B737NG [11]

same wing throughout the variants and fuselage plugs which enable scaling or “stretching” between the variants. Scaling the fuselage can also be seen as a subset of module-based product family design due to the addition of new modules to serve different market segments. These fuselage plugs do not change the diameter of the fuselage. Figure 18 shows the corresponding seat layout for each variant of the 737NG family to demonstrate fuselage stretching.

Additional fuselage plugs result in an increased operating empty weight (OEW). Also, due to additional passenger capacity, the payload is increased for a fully occupied flight. These two factors result in an increased TOGW, which as a result increases the wing loading when the same wing is utilized among the variants. This may compromise the fuel efficiency especially at the cruise condition. In Figure 19, it is possible to observe how the same fuel capacity and the same wing shapes the payload-range diagram as the fuselage is extended. Especially, the comparison of 737-700 and 737-800 payload-range limits exhibit how sharing too many common parts increase the payload capacity at the expense of reduced range capability. In this particular comparison, every derivative except 737-600 utilize an additional winglet and 737-900ER extended range version has a slightly

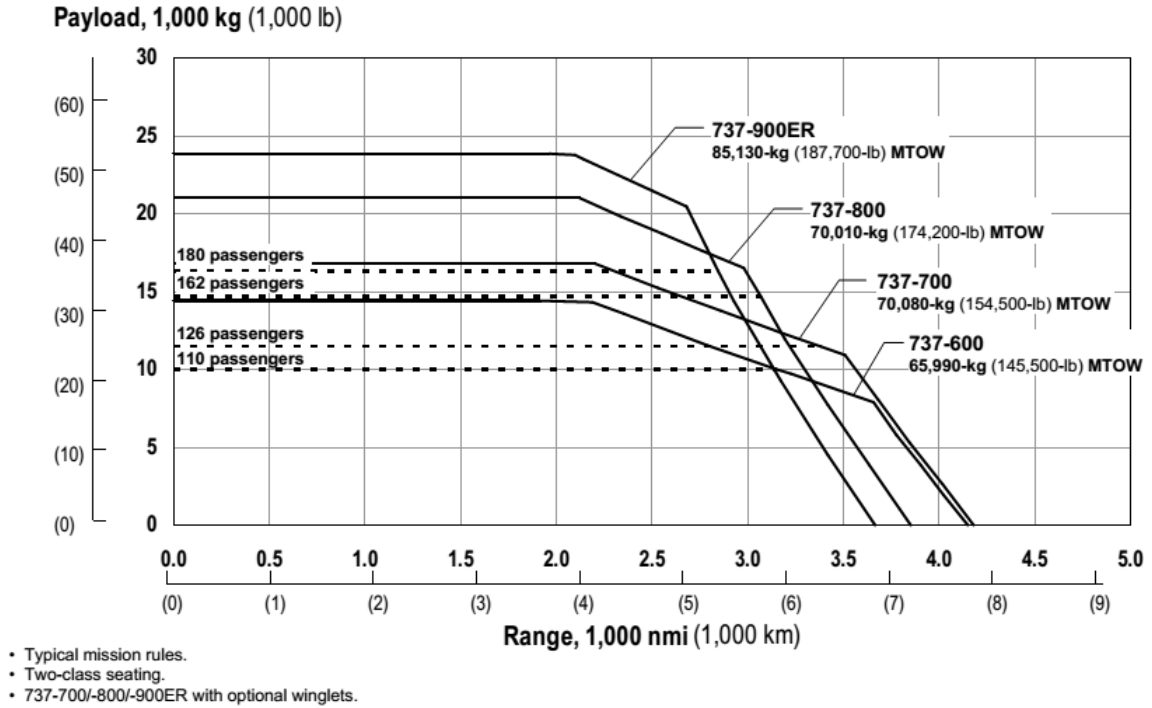


Figure 19: Payload and Range Diagram for B737NG Aircraft Family [11]

larger fuel tank which can still offer a relatively flexible range capability while extending the payload capacity. At this point, it is necessary to clarify that a larger payload-range envelope does not correspond to a higher operational efficiency, but it can clearly be an indication of high operational flexibility.

Most of the aircraft families, including the B737NG family, also share common empennage. However, the general trend of the need for a bigger wing as the TOGW increases is not easily applicable to the empennage sizing. Empennage sizing usually involves advanced stability, and control analysis, but in simple terms, the tail aims to counter the moments generated by the wing. Therefore, tail size is related to the wing size as well as the “moment arm”. Moment arm in this case is the distance between the tail and the wing which is mainly a function of the fuselage length. Raymer defines the tail volume coefficients for vertical tail and horizontal tail respectively as follows [169]:

$$c_{VT} = \frac{L_{VT}S_{VT}}{b_W S_W} \quad (1)$$



$$c_{HT} = \frac{L_{HT}S_{HT}}{C_W S_W} \quad (2)$$

Moment arms ( $L_{HT}$  and  $L_{VT}$ ) is approximated as the distance from the tail quarter-chord to the wing quarter-chord. Wing span ( $b_W$ ), wing area ( $S_W$ ), vertical tail area ( $S_{VT}$ ), horizontal tail area ( $S_{HT}$ ), and mean chord length ( $C_W$ ) are the other geometric properties used to estimate the volumetric tail coefficients. For jet transport aircraft, these values are listed at 0.09, and 1.0 for vertical tail, and horizontal tail respectively based on historical examples. At the conceptual design phase, these numbers can provide some simplified guidance to the stability, and control related needs of the vehicle defining the minimum requirements.

In the case of aircraft families, B737NG family uses the same empennage structure. However A320, B737NG's competitor in the narrow-body market, has two different tail designs among its members. The smallest A320 variant, A318, uses a larger tail than its bigger derivatives. This implies that the bigger derivatives do not necessarily need bigger tails partially due to the usage of the same wing and partially due to the advantage of having a longer fuselage which naturally increases the moment arm. Therefore, it is concluded that the tail should be sized according to the smallest derivative. To sum up, one can suggest that sharing the same empennage throughout the derivatives may perhaps result in an additional drag penalty for the bigger derivatives.

**Observation 5:** *Family members in most successful commercial aircraft family programs share the same empennage, wing, nose, cockpit, nose, and fuselage cross-sections (plugs). Addition of winglets is not uncommon.*

The wing design is one of the most costly elements of aircraft design. In the traditional aircraft design, the wing is usually sized for the most demanding condition of the design mission. For most designs, it is possible to argue that it is the landing phase. Unlike the empennage sizing for the families, the wing is usually sized for the biggest derivative in cases where multiple wing designs are not available, or seen as unprofitable in means of program economics.



There are exceptions to the common observation of sharing the same wing. In certain aircraft families such as Embraer E-Jet family, different derivatives use different wings. E-170 and E-175 have a smaller wing and horizontal tail than E-190 and E-195 although they still share the same fuselage plugs [13]. For the case of a fuselage extension, which is utilized in this thesis, several assumptions are made. Most of the modern narrow-body aircraft feature six-abreast cabin configurations. A logical assumption would be to assume passenger capacity for the 1-class dense configurations are increased by multiplications of six seats at all times.

$$l_f = l_{bf} + \frac{\Delta Seats}{6} \Delta l_{row} \quad (3)$$

Starting from the baseline fuselage length  $l_{bf}$ , and assuming six seats per row with  $\Delta Seats$  representing the number of seats difference, the new fuselage length  $l_f$  can be calculated using  $\Delta l_{row}$ . A linear regression based on 1-class, dense configurations of A320neo family members indicate an estimate of 91cm (~3ft) of fuselage extension per new row of six seats with an  $R^2$  value of 0.98. These values support the assumption of linear fuselage extension.

Engine selection among aircraft families is also an interesting topic. All of the aircraft manufacturers in today's commercial aviation market outsource the engine from three primary jet engine manufacturers: General Electric Company (GE), Rolls-Royce Holdings (RR) and Pratt & Whitney (PW). Although different TOGWs associated with different variants require different thrust levels from the engine. Aircraft manufacturers form partnerships with engine manufacturers, and utilize the same engine with different thrust ratings. This is to ease the process of design, certification, and maintenance while allowing flight crew compatibility. Aircraft engines are also designed as product families such as CFM International's CFM56 which have five series within its domain. B737NG is powered by CFM56-7 which have different thrust ratings ranging from 19,500lb of CFM56-7B18 to 27,300lb of CFM56-7B27 used in B737-600 and B737-900 respectively.

### ***3.3 Comparison of Commercial and Defense Market Systems vs Perfect Market Characteristics***

So far, a military aircraft family example (JSF) and a commercial aircraft family example (B737NG) have been introduced. Those sections dealt mainly with the physical architectures of the systems. When the primary concern is designing a vehicle platform that can be successful in the market competition, the observations should extend beyond the design to meet the requirements and consider the market systems. In this section, the aim is to identify some of the key differences between these markets. The differences are observed in:

- **Number of producers and buyers**

In a perfect market, there are many buyers and producers and none of them are dominant. In such a case, each buyer has many alternatives to choose from. Commercial aircraft market can be seen as an oligopoly for the narrow-body market (e.g. Boeing, Airbus, Embraer, Bombardier etc.), and a duopoly (Boeing, and Airbus) for the wide-body market. Defense market systems usually have only one buyer, and only one producer which is the prime contractor that develops the system (e.g. Lockheed Martin F-22 Raptor and United States Air Force). In such a monopolistic environment, the prices are determined by a series of negotiations.

- **Product differences**

In a perfect market, products are homogenous meaning they are existing, standardized items which are the same for each producer. Also, its characteristics are stable over time. In commercial aircraft market, products are relatively closer to each other in means of missions they can perform. This may be observed within the products of the same company (e.g. B737-600 can fly 108 passengers to 3050NM whereas B737-700 can fly 128 passengers to 3365NM) or between the companies (e.g. A319 can fly 124 passengers to 3600NM). This also indicates these products can be substitutable meaning an airliner company may buy a particular model instead of another if the conditions are favorable. For military acquisitions, product is a newly developed item without close substitutes. Also, the design evolves throughout the time with periodic upgrades.

- **Competition focus**

In a perfect market, competition focuses on price/quantity alone. In commercial market systems, buyer is concerned with the performance and the price of the market equally as well as many other factors such as buyer's origin, fleet commonality etc.. In the defense market systems, buyer is concerned mainly on the product performance as the price is not the dominant consideration in selecting the producer. Prospective producers compete in the early development phase through "design rivalry" (e.g. Boeing vs. Lockheed Martin in JSF program)

- **Technology and economies of scale**

In a perfect market, no producer has an advantage in production technology, or economies of scale. In the commercial market, Boeing, and Airbus possess equally extensive know-how, and equivalent production rates as compared to smaller companies such as Embraer and Bombardier. In the defense systems, production technology is dynamic, and may differ among prime contractors and their subcontractors. Economies of scale significantly influences the producer costs as production volumes are small.

- **Market entry**

In a perfect market, market is easy for new producers to enter. Commercial markets, and military markets have similar properties in market entry aspect as new companies rarely enter the market due to high capital investment required. Especially for the military markets, the administrative and contractual burdens of a highly regulated industry is a significant reason to prevent easy entry.

- **Acquisition process**

In a perfect market, buying the product is a simple, quick, one-step transaction between the buyer, and the producer. This process is independent of other purchases from the same, or other producers. In commercial aviation, this process is more complicated as "bidding", and "green stamps" are usually observed between different manufacturers [114]. Instant delivery is usually not possible, as especially in the narrow-body market, buyers are facing backlogs.

On the other hand, acquiring a military system is a multi-year, multi-step, complex process which requires many negotiations between the buyer and the producer.

- **Intelligence and uncertainty**

Perfect market is characterized by perfect intelligence, and absence of uncertainty. Information about product price, standards of quality, number of items to be purchased, delivery schedule etc. is available to all concerned. In both commercial and military markets, uncertainty is a dominant, and unavoidable reality. The uncertainty specific to LCA market is elaborated in Section 3.7.

**Observation 6:** *LCA market is an oligopoly with heterogeneous but substitutable products. Market also has various sources of inherent uncertainty.*

### ***3.4 Large Commercial Aircraft Market***

In this section, wide-body, and narrow-body markets will be differentiated. Based on the observations from the current market structures, the primary case study of this thesis will be on the narrow-body market since it involves more strategic interactions than the wide-body market due to potential entrants.

#### **3.4.1 Wide-Body Market**

The wide-body aircraft, also known as twin-aisle or large aircraft, market encompasses a wider variety of sub-segments where the most common classification is the small (180-340 seats), medium (260-450 seats) and large (>400 seats) wide-body aircraft. The duopoly competition can be observed clearly in the wide-body aircraft market where there is no threat of a new entrant soon. In means of strategies however, the duopolists Boeing, and Airbus have different visions of the future. Early 2000s saw these two companies deciding to come up with different products to serve the same market. Airbus's strategy with 550-seater A380 has been serving the congested hubs with less flights for the same amount of passengers so that the problems related to airport capacity are minimized. On the other hand, Boeing has introduced the B787 which has a capacity of 290 passengers so that more direct flights with fewer connections are encouraged. Initially, this could mean that

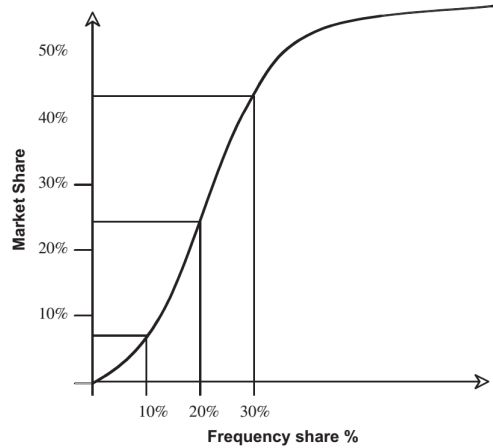


Figure 20: The Market S-curve [199]

the duopolists are following “complementary” strategies to each other. However later on, Airbus announced A350 which is an evolution of the A330 to compete directly with B787. In the same year of 2005, Boeing also announced it would stretch the existing B747 to create B747-8 Intercontinental which would compete with A380. These policies show that none of the manufacturers are willing to cede any part of the wide-body market to its competitor [138].

Uncertainty associated with the airline strategies to prefer less flights with more capacity or more flights with less capacity result in two types of uncertainty from the manufacturer’s point of view. First, the design requirements and market segmentation is subject to change because of these policies. Second, it alters the number of aircraft required, which results in different demand profiles. Airline strategies are usually explained by the frequency/market share S-curve [199]. In a certain Origin-Destination (OD) pair, when the same total daily transport capacity is distributed to more frequent flights, the market share of an airliner can be increased thanks to more options offered to attract more customers. This, however, usually comes at the cost of increased fuel burn per seat per mile. These are very complicated decisions that need to be carefully made by the airline managers and are out of the scope of this thesis. However, due to these reasons, especially in the wide-body market “mismatch” exists between the design missions of different vehicles and these vehicles are not quite substitutable as observed in the narrow-body market.

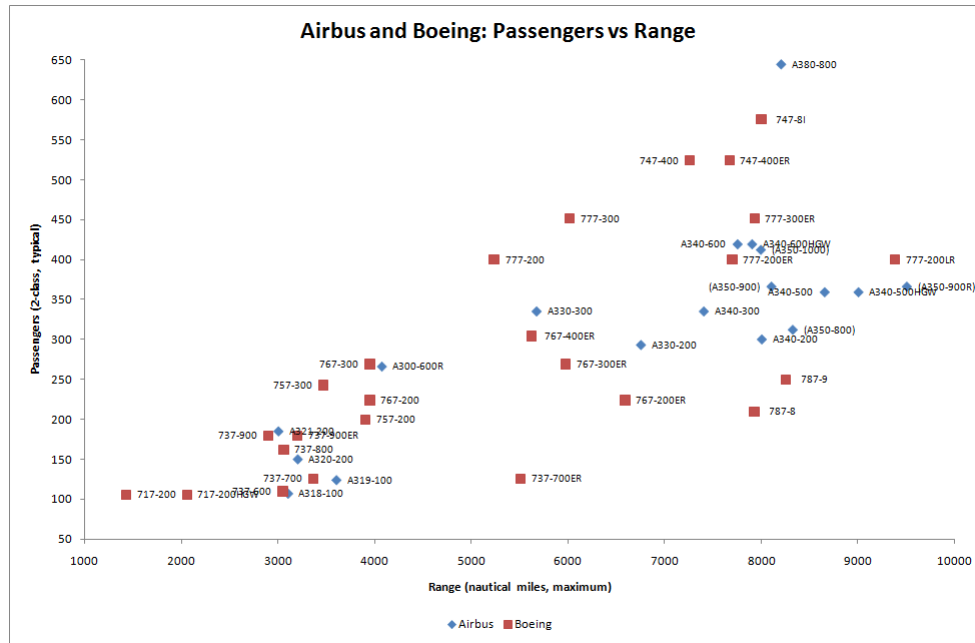


Figure 21: Airbus vs. Boeing Product Line Comparison [8]

Wide-body market is a small market in means of unit numbers with very expensive goods. Wide-body aircraft are also more expensive, complex and risky to develop. In the B787 Dreamliner program, Boeing experienced production delays, supplier delays, cost overruns and technical problems which increased the development cost from the initially planned amount of \$5 billion to \$12 billion [23]. This huge jump in R&D costs is attributed to the extensive use of composite materials, new wing design, new flight deck technologies etc.. Similarly, Airbus A380 was initially thought to cost \$8 billion to develop, but the final cost rose to \$12.2 billion [16].

**Observation 7:** *Extensive R&D effort required results in massive entry costs and this prevents smaller firms without sufficient know-how and capital resources to enter the market. Entry cost is also a source of uncertainty as many airframe development programs tend to take longer and cost more than the initial plans. In any scenario though, utilization of a common platform across segments allows reduced average entry costs per design.*

The existence of relatively high entry costs, and uncertain capacity/frequency demand is not unique to the wide-body market. However, it is easier to observe these occurrences in the wide-body market rather than the narrow-body market. This is the main reason, this

Table 4: Boeing and Airbus Narrow-Body Comparison [85, 158]

Aircraft Type	Seats	Range (NM)	Aircraft Type	Seats	Range (NM)
B737-600	110	3050	A318-100	107	3100
B737-700	126	3365	A319-100	124	3600
B737-800	162	3060	A320-200	150	3100
B737-900ER	180	2700	A321-200	185	3000

section focused mainly on these observations. As explained, one of the significant differences is in the similarity of the segmentation. As shown in Figure 21, the biggest difference is in the way Boeing and Airbus attempt to satisfy the needs of the customers in the wide-body market.

### 3.4.2 Narrow-Body Market

Narrow-Body, also known as single-aisle aircraft, market is defined to include LCA that have more than 90 seats. This is not a strict definition however, as the smaller jets such as Regional Jets (RJ) which are traditionally known to accommodate up to 90 passengers recently have some models from Bombardier and Embraer that can seat up to 100 passengers and more. Historically, Boeing 737 and Airbus A320 families define the market. Defining the market is not only dominating this high concentration market, but also defining the exact requirements for these aircraft as a norm for potential entrants, setting the standards. The “mismatch” in the design mission capabilities of wide-body aircraft offering airlines multiple passenger-range combinations does not exist in the narrow-body market. The products from these two companies are easily comparable to each other.

This high substitutability between the aircraft from different manufacturers due to similar design missions intensifies the competition between the companies and enhances it both in means of price discounts and increased technical benefits despite the duopoly. Also, the competition is not necessarily between two different companies. The empirical studies indicate that lowering the prices of a certain model attracts customers that would initially go for another model of the same company [103]. This may be observed within the same market and also very rarely, this can be observed across the segments. This cross-price elasticity phenomenon will be elaborated in Section 4.1.2.

Table 5: Projected Narrow-body Production Rates for 2018 [3]

Company	Per Month	Annually
Airbus	42	462
Boeing	42	504
Bombardier	10	120
Embraer	17	204
COMAC	5	60
IRKUT	5	60
Total	121	1410

An interesting observation from the narrow-body market is the observation of backlog. Backlog is a natural outcome of capacity constraints, and significant growth of narrow-body market, especially in regions like Asia Pacific. The high amounts of backlog observed is a hot topic for debate. Some experts argue that the current production rates of Boeing and Airbus which are about 42 aircraft per month doesn't balance supply and demand as based on the forecasts, the demand is 30 aircraft each per month from these manufacturers [3]. This is based on the projected forecasts of narrow-body production rates as shown in Table 5. Capacity constraints haunting the narrow-body market may propose advantages to the entrants as fast-growing airlines will prefer to expand their fleets earlier and may go for readily available aircraft. In this framework, backlog will not be modeled due to its questionable impact although the poor management of capacity can lead to reduced program value as it may cause production surplus planes called "white tails" or insufficient supply to the customers.

In addition to these observations, it is also interesting to recognize the need for vehicle-infrastructure compatibility for the design of future vehicles [108]. Advisory Circular 150/5300-13 of Federal Aviation Administration (FAA) categorizes aircraft into different classes [61]. These classes impose geometric constraints on the dimensions of the vehicles to ensure safe ground operations. All of the aircraft within the narrow-body families considered here (B737NG, B737MAX, A320, A320neo) fall within the Airplane Design Group (ADG) Category 3. These categories are defined by the following:

There are certain consequences of not matching the current ground operation standards of the fleets of families that are to be replaced. One direct result is a compromised ground



Table 6: FAA Airplane Design Groups for Airport Design [61]

	Airplane wingspan	Tail Height
Group I	< 49' (15m)	< 20' (6.1m)
Group II	49' (15m) - <79' (24m)	20' (6.1m) - <30' (9.1m)
Group III	79' (24m) - <118' (36m)	30' (9.1m) - <45' (13.7m)
Group IV	118' (36m) - <171' (52m)	45' (13.7m) - <60' (18.3m)
Group V	171' (52m) - <214' (65m)	60' (18.3m) - <66' (20.1m)
Group VI	214' (65m) - <262' (80m)	66' (20.1m) - <80' (24.4m)

utilization, which may result in access to fewer airports both in US, and around the world. International Civil Aviation Organization (ICAO) Annex 14 lists similar geometric constraints including the wingspan, and the outer main gear wheel span [34]. In this thesis, all of the future vehicles are forced to have wingspans lower than 118ft, and a tail height of 45ft, thus falling within the ADG III. This will ensure that the new vehicles can directly replace the existing fleets without requiring further infrastructure arrangements. These geometric constraints are easier to model, and implement unlike some other complex drivers. An example to those complex elements could be the airlines' preference towards similar cockpits, which airlines prefer for crew scheduling purposes.

Specifying the common platform modules to the wing, and the empennage ensures all family members will be within the same ADG per FAA's classifications. For the scope of this thesis, it is very difficult to estimate how an increased ADG would affect the market performance of the family member. However, the justification for this constraint is that as long as all family members are in the same group, competitiveness of the products should not be affected. In fact, since the common platform is fixed at a common wing, and empennage, the constraints imposed ensure the family members stay in the same group. However, the tail height is an indirect constraint governed by Equation 1 and 2 to ensure sufficient stability, and control power.

### ***3.5 Economies of Scale and Economies of Scope***

Klepper summarizes the LCA industry characteristics in three main elements[120]:

- **Static economies of scale:** Includes R&D and start-up investment

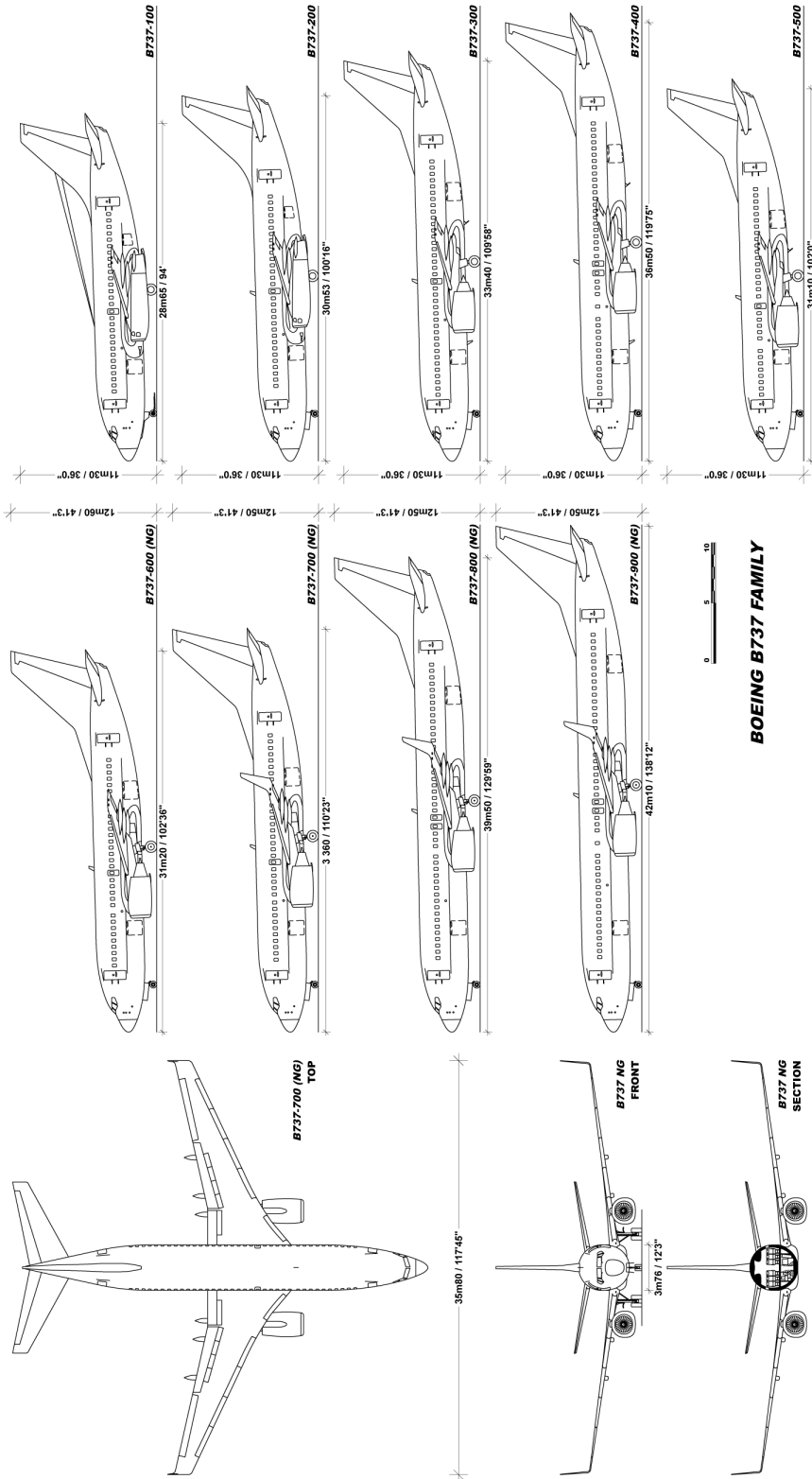


Figure 22: Dimensions of the B737 Families [11]

- **Dynamic economies of scale:** Includes LBD
- **Economies of scope:** Includes family cross-effects

Economies of scale are the set of factors that result in reduced average unit cost as the production volume increases whereas economies of scope, as often related to the economies of scale, are the set of factors that make it cheaper to produce a variety of products together instead of producing each one of them on its own independently [99]. The fundamental contribution to the economies of scale in aircraft industry comes from the learning effect which is usually modeled with a learning curve [169]. Each time the cumulative production quantity doubles, the production time and cost will be a certain percentage of its value before the doubling occurs [35]. A typical power-function for the learning curve is [136]:

$$\gamma = ax^{-b} \quad (4)$$

where

- $\gamma$  is the number of direct labor hours required to produce the  $x^{th}$  unit
- $a$  is the number of direct labor hours required to produce the first unit
- $x$  is the cumulative number of units produced
- $b$  is the parameter measuring the rate labor hours are reduced as cumulative output increases

Benkard indicates that the smooth learning curves used in analyzing LCA industry lack in explaining the complexity of the actual dynamics and suggests the presence of “Learning and Forgetting” and the stochastic evolution of learning [42]. In this thesis, in which one of the primary aims is to assess the commonality benefits, this is an element that can’t be disregarded and will be incorporated. Apart from these production benefits, static economies of scale are fairly straight-forward: the total non-recurring cost in the form of initial investment is divided by the number of total units produced. In this case, the initial investment is assumed to be independent of the total production volume.

Aircraft families offer huge commonality benefits in both economies of scale and scope. Shared parts throughout the entire family means a single type of part can be used across a greater market share. This brings learning curve effects at a part level, if not the vehicle level. Unique advantages for commonality also come in economies of scope. Baldwin and Krugman explain the difficulties faced by A300 not only by the late entry which results in a hard progress on the learning curve, but also lack of a complete product line extending to A320 family, and A330/A340s [39].

### ***3.6 Market Entry***

Firms consistently have to answer three main questions with regards to market entry [91]:

- **What market to enter?:** Entry location
- **How to enter?:** Mode of entry
- **When to enter?:** Timing of entry

In the light of these questions, the new entrants to the aircraft market face a number of challenges which may result in quitting the program, reconsidering the design or discovering successful strategies to make profits in a competitive environment. Entry usually refers to the entry of a new company. However, it may also mean the introduction of a new vehicle by a company which is already in the market. Following the terminology of market entry, there are two incumbent firms: Boeing, and Airbus. Identifying the entrants is not a straightforward task as they are not physically present in the market. Based on the available data, today's potential entrants include firms from four different countries. Russian, Chinese aircraft manufacturers have not built a competitive large commercial aircraft yet. However, Bombardier of Canada and Embraer of Brazil have manufactured regional jets with success. The brief summary of the entrants as of 2011 is as follows [94]:

- **Bombardier CSeries (Canada):** CS100 targets B737-600/B-737-700 (A318/A319) segment whereas CS300 seats between 125-145 passengers to compete with B737-700 (A319) class.

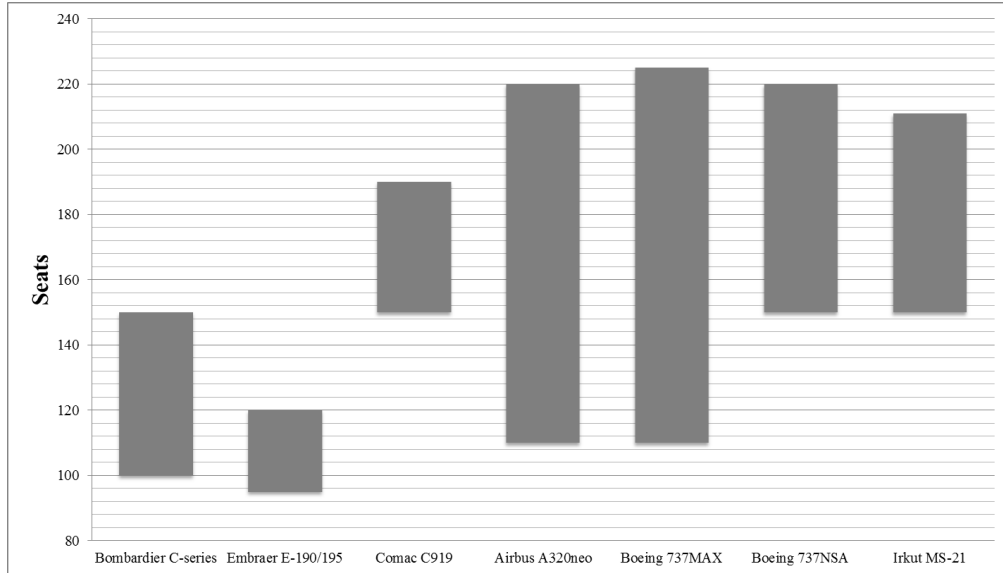


Figure 23: The Future of the Narrow-body Market [19]

- **Embraer (Brazil):** E-190 and E-195 currently compete with the B737-600 (A318) segment.
- **COMAC C919 (China):** C919 is in the same segment as B737-800 (A320). According to Boeing’s forecasts, China will take delivery of approximately 16% of the world’s total airplane deliveries until 2032 [18].
- **UAC/Irkut MS-21 (Russia):** MS-21-200, MS-21-300 and MS-21-400 target B737-700, B737-800 and B737-900ER (A319, A320 and A321) segments respectively. First delivery is expected to be between 2017 and 2020.

Considering these two companies who have proven themselves in the industry with regional jets (RJs) and other two who are supported by their governments, Airbus and Boeing duopoly is under a challenge. John Leahy, COO-Customers of Airbus, has stated: “Airbus was not going to make the same mistake with Bombardier that Boeing did with Airbus—that is, not to take the threat seriously.” [2]. This implies that the incumbents are aware of the threat, and the competitive pressure from the potential entrants.

The next question perhaps is: “Is the narrow-body market large enough to sustain all these manufacturers?” For this purpose, several different forecasts are examined. Boeing

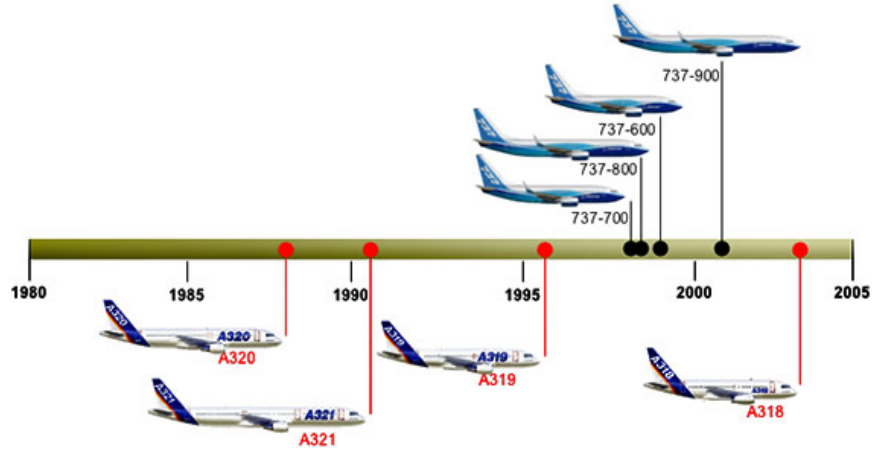


Figure 24: Timeline of Introduction of B737NG Family vs A320 Family [11]

projects delivery of 25680 narrow-body aircraft over next 20 years as Airbus forecast indicates 22070 deliveries [158, 85]. High number of units and relative ease of entry makes it a clear opportunity for entrants to recover sunk costs in the narrow-body market. Also, the narrow-body demand is higher than the current percentage of narrow-body aircraft in service.

**Observation 8:** *LCA demand is volatile. At the same time, aircraft are expensive, and durable goods; but the market is small in means of number of units.*

The brief company outlook presented represents “the mode of entry”. The question of “When to enter?” is another important issue. For a given vehicle with fixed level of technology, it is intuitive to think that a firm will try to enter the market as soon as possible to prevent the introduction of an out-dated product. But then, the next question is “Which derivative should be the first one to introduce?”. Even when all derivatives are kept in mind when designing the product platform, manufacturers try not to delay the introduction of their products. A particular example to this is possibly the introduction of B737NG family to compete with A320 family as shown in Figure 24 [11]:

**Observation 9:** *Simultaneous introduction of multiple derivatives at the same year may technically not be possible as manufacturers usually finalize a baseline design and continue to work on the derivatives. In any case, using a common platform greatly reduces the time to market.*

### **3.7 Uncertainty**

The production of a commercial aircraft can only begin after years of extensive R&D which usually averages about 5 to 6 years[119]. For example, the first Boeing 737-200 was introduced to service in 1968, and was flying scheduled routes until 2008. Since commercial aircraft stay in the market for such long durations, the designer must consider the entire lifespan of both the vehicle and the program. For the scope of this framework, the uncertainty related to the program lifecycle is the main focus as the manufacturer must ensure that there is always a market of reasonable size so that at least the development costs or other sunk costs for the program are covered.

From the airliner point of view, the operational costs come from different sources. Some of the primary elements of costs are fuel, maintenance costs, crew salaries and benefits, landing fees, depreciation and amortization. Some of these cost items are highly relevant to the technical characteristics of the aircraft. Therefore, realizing the needs of airlines as well as the related uncertainty and projecting them to the conceptual design phase is critical to ensure robustness.

#### **3.7.1 Systemic Market Risk**

Exogenous risk for commercial aircraft programs comes from various sources. These two elements are considered:

- **Overall market demand**
- **Fuel Prices**

The demand for commercial aircraft especially in the narrow-body market is a source of uncertainty. The number of aircraft deliveries per year is correlated to various factors such as Gross Domestic Product (GDP) growth, population growth and demand for air transportation in general which is hard to estimate due to its dependence on many exogenous elements such as cultural factors. Decision-makers constantly try to have the most accurate predictions by monitoring the changes so the market size can be estimated to follow more profitable strategies. Due to the complexity of this estimation, manufacturers usually come

up with forecasts that are inconsistent with each other [85, 158]. As explained in Section 3.7, demand volatility is not only attributable to the growth of the vulnerable airline industry but also the trends in air travel in general. Different airlines have different views on the issue of smaller airplanes with higher frequencies or larger airplanes with less frequencies (usually using main hubs). As an example, Boeing believes the hubs will be more and more congested to become too expensive to operate within whereas Airbus forecasts, based on an analysis of 20-year, that the airlines will need larger aircraft to effectively utilize major hubs [98]. Boeing believes travelers will prefer non-stop flights between smaller hubs. If Airbus's predictions hold, especially for the wide-body market, A380 will be more successful than the smaller B787. Due to such cases, the interest should not only be in the growth of the market, but also the demand shift between different vehicles.

Future delivery forecasts are usually continuous. Although the possibility of a new market entrant can significantly change the number of aircraft delivered for an incumbent firm, this section deals with how the overall demand, that is the number of total deliveries by all companies combined, changes. To capture the uncertainty of deliveries, a mean reverting process in the guidelines of Blanco is commonly seen in literature. Their model can be shown as [149, 46]:

$$X_{t+1} - X_t = \kappa(\mu - X_t) + \sigma\varepsilon_{t+1} \quad (5)$$

In this model, the expected change in demand ( $X_{t+1} - X_t$ ) is a function of:

- $\kappa$  is the speed of adjustment coefficient
- $\mu$  is the long run mean value of annual percent change in deliveries
- $\sigma$  is the demand volatility
- $\varepsilon$  is the value of random, independent shock

In the absence of “game-changing scenarios, these models tend to work reasonably well so, this is an underlying assumption for using such simplified approaches. Fuel prices also tend to affect the airliner's choice of aircraft. Fuel price forecasts are important from the



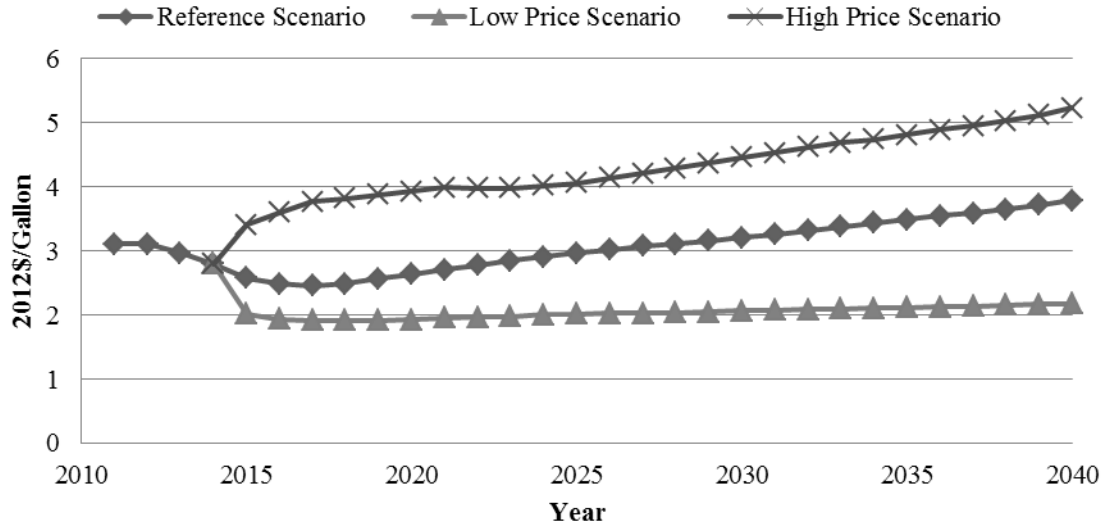


Figure 25: Fuel Price Forecast including Low, Expected, and High Scenarios [26]

manufacturer point of view as airlines prefer more fuel-efficient aircraft as the fuel prices are higher. In those circumstances, the acquisition cost of the aircraft may be less important. As aviation relies on fossil fuels and the sources are getting depleted, it is natural to expect a continuous rise on the jet fuel prices. Three different scenarios from US Energy Information Administration are shown in Figure 25.

Changes in fuel prices are addressed in many studies that try to balance engineering, and marketing considerations. It is an important element of airliner's perception of the attractiveness of a design therefore important for manufacturers. Manufacturers often face tradeoffs between the fuel efficiency, and the R&D, and production cost of vehicles. Even in studies without the competitive analysis, these studies are critical in minimizing the LCC of a product, and therefore increasing its attractiveness to customers.

### 3.7.2 Firm-specific Idiosyncratic Shock

Shock refers to the realization of different states of the world [122]. Firm-specific shocks, also known as idiosyncratic shocks are independent of the market, and specific to firm's internal structure, and dynamics [76]. It is possible to identify three components of idiosyncratic shocks:

- **Uncertainty within customer perception of the product:** One possible reason for an idiosyncratic shock can be a quality control issue that results in defected products. Although not very likely, accidents, or regulatory changes can also affect the market performance of a vehicle, and can occur at any time period during the program's lifecycle.
- **Uncertainty within the entry (R&D, and facility) cost:** Recalling the Observation 7, another possible source of firm-specific shock is the entry cost. Although every R&D program is cursed with certain amounts of uncertainty, it is possible to expect firms with no previous aircraft production experience to expect higher expected values and an increased deviation in the distribution. These factors are recognized as firm-specific elements within this framework.
- **Uncertainty within the scrap value:** The third source of a firm-specific element of uncertainty is the usage of scrap values. Previously, two aircraft in the same discontinued narrow-body sub-segment were given as examples: B737-600, and A318. Although, not many data is available about these types of inside information about firm decisions, it is possible that these products are discontinued in the next generations because of low order numbers. This implies that even though the R&D effort is put in and the firm has the capability to produce these vehicles at no cost, it is economically more profitable to stop production, and receive a scrap value. From the simulation perspective, these values would enable the decision-makers to identify segments that are no longer seen profitable. Without such a definition, firms would keep offering products in those segments as they have nothing to gain by stopping the production. Considering the actual practices, it is intuitive that aircraft manufacturers will recover some of the production tools, and facility resources after the production is halted.

### **3.8 Formal Problem Formulation**

In this research effort, the main problem arises from the need for incorporating quantitative approach with a qualitative philosophy. The fundamental philosophy is motivated by the

observations from the industry: the success of an aerospace program does not solely depend on the quality of the design, but also the management of the program throughout its entire lifecycle. When this problem is extended to include the competition between multiple firms, systemic market risks, and idiosyncratic shocks, it can become complicated quickly for anyone who attempts to quantify these elements. As shown in the next chapter, the existing research efforts were usually insufficient to cover certain fundamental elements of the LCA market.

Based on the literature review, and observations from the industry, a large-scale aerospace program consists of three types of decisions: design decisions, financial decisions, and economic decisions. When the problem of maximizing the expected program value by making design changes at the conceptual design phase is considered, designers need better decision-making tools. This need is caused by two main requirements:

1. Early in the design phase, little information is available about the future of the firm itself, the market, and the competition
2. The product platform to be designed is very likely to stay in the competitive market for at least two decades

From the designer perspective, when consecutive effects of technical design decisions are considered within the marketing perspective, the influences are numerous. These technical decisions may influence the customer's purchasing behaviors, and firm's growth opportunities, as well as strategic benefits to the nation. Since the consequences are widely spread, a variety of different approaches are encountered in literature. For any of these examples, the generalized form of a mathematical notation is given by Papalambros [161]. The expanded form to account for product families is as follows:

$$\Pi(x), x = [x_d, x_b], x_d = [x_c, x_u], x_b = [x_e, x_f]$$

where  $\Pi$  is the profit (value in this thesis case, however the original notation is used),  $x$  is the set of product decisions that encompasses engineering design decisions  $x_d$ , and business decisions  $x_b$ . Engineering design decisions  $x_d$  includes common design attributes  $x_c$  that are shared throughout the family, and unique design attributes  $x_u$  that are derivative specific.

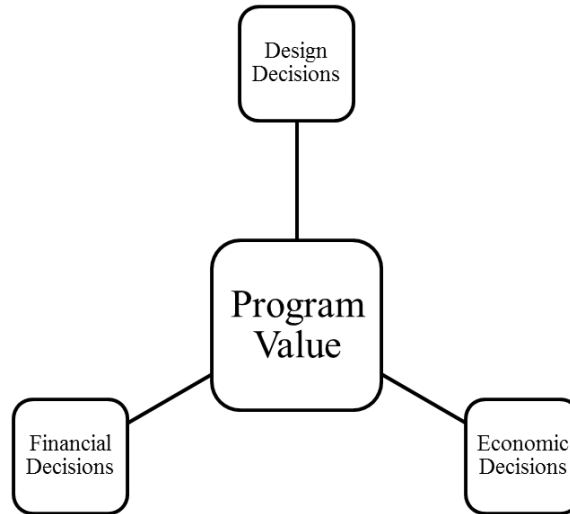


Figure 26: Controllable Elements for Achieving Program Value

Business decisions  $x_b$  is composed of economic decisions  $x_e$ , such as product pricing, and output quantity decisions, and financial decisions  $x_f$  such as investment timing and value considerations.

**Research Question 1.a:** *What are the main types of actions controllable by the aircraft manufacturers before and after entering the market?*

Reconsidering the Research Question 1.a, it is now possible to answer the question based on both the observations, and the literature review. The specific area to answer this question to be found in the literature review was the means of strategic flexibility used by top-level decision makers in the industry. Resource flexibility, and coordination flexibility, explained in Section 2.9, are identified as keys to market success. Based on the assumption of fixed variants, the design specifications reduce to common design attributes, which are the product platform specifications. Once the platform is fixed, and the market is entered, managers can still decide on the strategic control variables (price, or quantity), and to enter/exit certain segments. In simple terms, the program value is a function of the firm's design decisions, economic decisions, and financial decisions.

Underlying assumption is that the design decisions are fixed once the product platform is utilized in the market. However, the managers can still control the program as suggested

in Observation 4. Among these, economic decisions can only be made once at least one of the family members is in the market. On the other hand, financial decisions, decisions that involve market entry/exit decisions, are made at every stage throughout the lifecycle, both before, and after the market entry.

As previously suggested, the main focus of this thesis is on the elements of conceptual design which is shown in bold. A market-focused designer should not only work on the elements of technical feasibility, but also the economical viability of a commercial program. Considering the certain control variables defined to answer Research Question 1.2, economic decisions, and financial decisions are made out of the control of the designer. In certain conditions, it may be possible to argue that there is an optimal combination of  $\mathbf{x}^*$ , composed of  $\mathbf{x}^d$ ,  $\mathbf{x}^e$ , and  $\mathbf{x}^f$ , that results in  $\Pi^*$ . At this point, considering the tools at designer's disposal, let's assume that the economic, and financial decisions will automatically react optimally to any design changes made by the designer to maximize the program value. This would allow the designer to see how design changes would result in an environment where there are obvious interactions between different decisions made even within a single firm. This is not a straightforward task as uncertainty, and competition affects decisions at all levels of the commercial program. The observations help answer the Research Question 1.b.

**Research Question 1.b:** *What are some of the key features of the Large Civil Aircraft (LCA) market?*

LCA market has the following main sources of uncertainty:

- **Systemic Market Risk**
  - Overall Market Demand
  - Jet Fuel Prices
  
- **Firm-specific Idiosyncratic Shock**
  - Uncertainty within customer perception of the product
  - Uncertainty within the entry (R&D, and facility) cost
  - Uncertainty within the scrap value (for exiting the market)

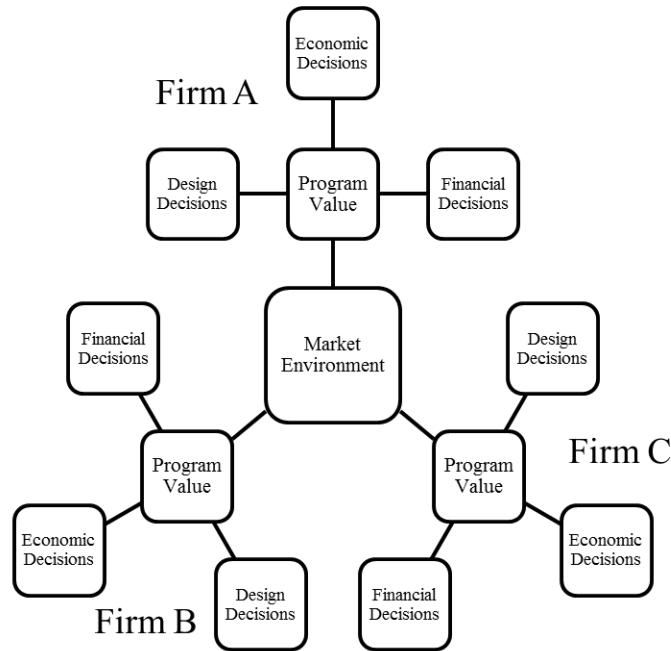


Figure 27: The Interaction of Decision Makers in a Competitive Market Environment

- **Competitive Reactions**

Here, possible competitive reactions are also listed as a source of uncertainty. It is intuitive to think so, as a given firm has no control over the actions of the competitors, and competitive reactions can affect the outcome of the objective of a firm, the program value in this case. However, in a game-theoretic sense, the competitive reactions are not completely random under certain assumptions. Those assumptions are listed as the motivations of the firms in this section.

In fact, in a dynamic, and oligopolistic market environment as shown in Figure 27. All decisions are interconnected, both within a firm, and between firms via the market environment. Since most of these decisions are observable and firms are non-cooperatively focusing on their own benefits, if a firm changes a decision, rational decision-makers are expected to react.

Key elements of LCA market are identified with the observations, and literature review. To summarize the key characteristics of large commercial aircraft industry, the following observations are identified:

**Observation 1:** *Aircraft production is the first published case of Learning by Doing (LBD) also known as the learning curve. Economies of scale are enormous relative to small market demand. Recurring costs are reduced through utilization of similar parts across different vehicles.*

**Observation 2:** *Static models fail to represent some of the observations in the LCA industry.*

**Observation 3:** *Creating a common platform to satisfy a diverse set of customer requirements may result in reduced program value.*

**Observation 4:** *Managers of aircraft family programs can still actively be involved and make value-adding decisions after the design is fixed. For different programs, there are different means to reach that goal.*

**Observation 5:** *Family members in most successful commercial aircraft family programs share the same empennage, wing, nose, cockpit, nose, and fuselage cross-sections (plugs). Addition of winglets is not uncommon.*

**Observation 6:** *LCA market is an oligopoly with heterogeneous but substitutable products. Market also has various sources of inherent uncertainty.*

**Observation 7:** *Extensive R&D effort required results in massive entry costs and this prevents smaller firms without sufficient know-how and capital resources to enter the market. Entry cost is also a source of uncertainty as many airframe development programs tend to take longer and cost more than the initial plans. In any scenario though, utilization of a common platform across segments allows reduced average entry costs per design.*

**Observation 8:** *LCA demand is volatile. At the same time, aircraft are expensive, and durable goods; but the market is small in means of number of units.*

**Observation 9:** *Simultaneous introduction of multiple derivatives at the same year may technically not be possible as manufacturers usually finalize a baseline design and continue to work on the derivatives. In any case, using a common platform greatly reduces the time to market.*

These observations impose certain requirements to any researcher that aims to model the LCA industry. Based on each observation, the following requirements are defined:

1. The ability to model economies of scale in a dynamic environment, and expand this ability to account for shared commonality between the family members.
2. The need for a dynamic model. In this context, the word “dynamic” has two meanings: The time dependence of decisions, and the strategic interactions between the firms.
3. Commonality may not always be beneficial for increasing the program value. Therefore, the marketing, engineering, and manufacturing aspects of the problem should be analyzed concurrently in a dynamic, competitive environment.
4. As defined in Chapter 2, increased program value through flexibility comes from two components: resource flexibility, and coordination flexibility. Coordination flexibility involves the actions of program managers after the vehicle platform is fixed, and is seen to be an important factor for successful aerospace programs. This type of a strategy space should be included in the model.
5. Observing the practices of existing conventional tube&wing aircraft manufacturers help reduce the design space by providing a priori knowledge.
6. LCA market features many buyers, and few heterogeneous producers with system-wide, and firm-specific sources of uncertainty. The design methodology needs the ability to model, and simulate the competitive interactions, and rational handling of uncertainty.
7. Entry cost should be modeled as an uncertain consequence of the decision to enter the market. A framework should also account for potential programs that seem to be profitable in the beginning, but prematurely end in a loss due to higher entry costs than anticipated, and/or unfavorable market outcomes.
8. As suggested in Observation 6, one of the main sources of uncertainty in the market is the volatility of demand. This happens at the overall market demand level, and product-specific level as firm-specific shocks may alter the customer value perception of vehicles.



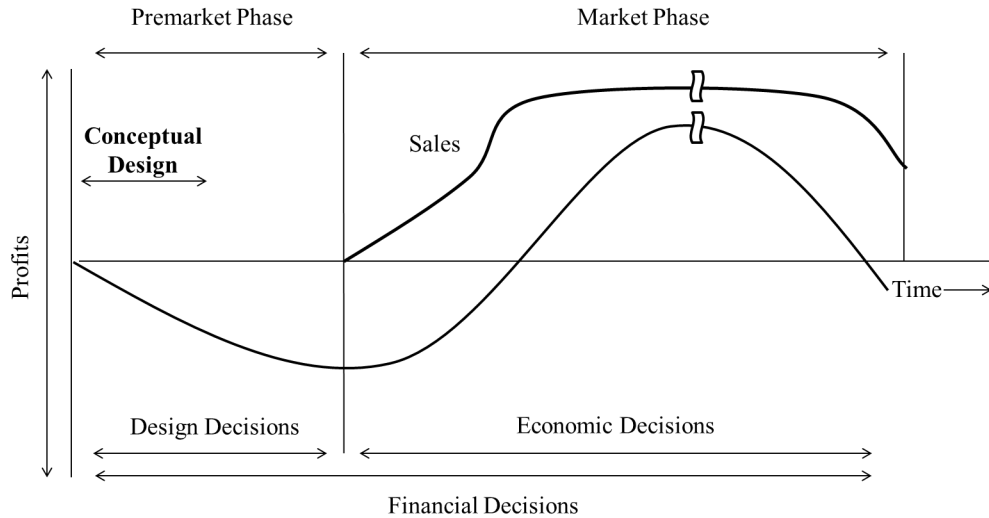


Figure 28: Design, Business, and Financial Decisions throughout a Program Lifecycle

9. Firms should come up with a strategic plan to introduce family members to the market in a sequential manner if entry is found to be viable.

Chapter 4 is dedicated to presenting the literature review conducted to identify a model that can simultaneously capture these industry dynamics. Therefore, it is possible to say that the observations define the requirements of a model to be found, but the model is not selected yet. This is the motivation for the next chapter. Finally before readdressing the primary research question, and listing the necessary assumptions in an attempt to find an answer, Research Question 1.3 can be rechecked.

**Research Question 1.c:** *How can we define the value from the aircraft manufacturer point of view? Once it is defined, what are the enablers to quantify it?*

Research Question 1.c is partially answered in Section 2.7, and in fact the second part of this question resonates with the secondary research question. The way to quantify the value is only possible via a comprehensive, and transparent model that can represent the industry-specific dynamics.

**Research Question 1:** *For a given oligopolistic market system with inherent uncertainty, how can an aircraft manufacturer estimate the expected family program value? How can we use this valuation technique to assess program risk of a new design?*

Modeling and simulating a competition to identify valuable designs is a difficult task. Any research attempt addressing this area needs clear assumptions. First, assumptions related to firm's behavior is explained. Aircraft manufacturers as players have the following characteristics:

- **Firms (both incumbents, and entrants) have similar expectations of exogenous uncertainty:** Although firms may be subject to different shocks, they have similar expectations of market-wide uncertainty such as demand fluctuations. No firm has the perfect information, or complete confidence about the future. It is assumed that they all observe similar forecasts.
- **Firms do not enter the market if an economic return is not anticipated:** This assumption is critical to limit the number of firms to a finite value, as market can only sustain a certain amount of players. This assumption is also easy to justify from a realistic perspective as firm theory suggests that the firms exist to generate value.
- **Firms are value-maximizers:** Firms will follow the policies that result in a maximized expected value metric. Value metric in this case is the profit.
- **Firms act rationally:** Firms behave according to rational expectations.
- **Firms play strategically with long-term goals:** Instead of myopic, short-term profits, the firms focus on the overall goals for the entire program lifecycle.

It is possible to argue that these assumptions do not differ significantly from the actual motivations of existing firms, though one critical aspect about these assumptions is the reality of the incumbent firms, to possibly deter new entrants at all costs. In this thesis environment, incumbent firms will do anything to maximize their program values. Most of the time, it is logical to expect these firms to try to prevent the new entry at the expense of short-term benefits.

Once the motivations of the firms, which are players(or agents), are defined, the second step is to define the structure of the market.

In this framework, firms compete in prices (Bertrand competition), instead of quantity and the price is chosen as a control variable. The literature is divided between whether the aircraft manufacturers compete in price, or quantities, therefore any preference is acceptable. Also, choosing price as a control variable will allow an easier interpretation of the values and is more intuitive. One drawback of such an approach though is that the direct mathematical implementation of the capacity constraints is no longer possible. Therefore, production capacity is assumed to be fixed and sufficient throughout the program lifecycle. In this framework, the simulation of backlogs is not included, and all the deliveries are assumed to be immediate. If there is a demand for a certain number of vehicles, then the delivery is made within the same year as the demand. Also, as shown in Equation 12 of Chapter 4, the revenue for the production is collected in the same time period with the demand, and the production. This assumption can be justified by the fact that many aircraft manufacturers will not be likely to produce “white-tails” without a guaranteed, fast payment.

Several authors such as Irwin and Pavcnik have analyzed the interactions between narrow-body, and wide-body markets [103]. Some of these results are shown in Table 7. Although significantly getting weaker within each time period analyzed, there is some price elasticity relation between these two markets. Within this work, wide-body aircraft are considered to be outside-goods, and any sort of relationship is neglected. A similar assumption is also valid for the Regional Jet (RJ) market.

Airlines usually prefer similar cockpits, and therefore same families, to ease the crew scheduling. This is hard to model due to lack of data to help understand how favorable the conditions become for airlines to make a certain aircraft more attractive than its competitors. In this thesis, this aspect, although recognized to be significant in the real life acquisition practices, is ignored. Similarly, long-term good relationships between airlines and manufacturers may result in more likelihood of continuing business together, this is also ignored in the case study.

## CHAPTER IV

### LITERATURE REVIEW AND FRAMEWORK DEFINITION

This chapter presents the findings of a more specific literature review, and proposes a framework that can be used to answer the research questions, and test hypothesis.

#### 4.1 Literature Review

##### 4.1.1 Market Share Attraction Models

Purely theoretical approaches are destined to reach certain limitations due to inability to come up with realistic representations of the industry in practice. At that point, empirical models can bridge the gap between the theory and practice by providing meaningful conclusions from the real-life data. That being said, high quality, reliable data is required to suggest and calibrate an acceptable model.

Several sources have tried to model the LCA market before. Recognizing its strategic importance, US International Trade Commission and National Aeronautics and Space Administration (NASA) have attempted this to assess the global competitiveness of US aircraft [32][201]. Market share is usually regarded as a very useful indicator of the competitiveness of a product or the producer. If a market entry is considered, these studies can help measure the economic impact of a product even in the early design phases. According to Owen and Naert, there are three types of market share models [159, 153]:

$$S_{it} = \alpha_i + \sum_{k=1}^K \beta_k X_{kit} + e_{it} \quad (6)$$

$$S_{it} = e^{a_i} + \prod_{k=1}^K (X_{kit})^{\beta_k} e_{it} \quad (7)$$

$$S_{it} = \frac{e^{a_i} + \prod_{k=1}^K (X_{kit})^{\beta_k} e_{it}}{\sum_{i=1}^I [e^{a_i} + \prod_{k=1}^K (X_{kit})^{\beta_k} e_{it}]} \quad (8)$$

where:

$t$	is the time period $t$ is the producer $i$ , $i=1,2,\dots, I$
$K$	is the total number of predictor variables
$S_{it}$	is the market share of producer $i$
$\alpha_i$	is the constant term of producer $i$
$\beta_k$	is the coefficient for the $k^{th}$ predictor variable
$X_{kit}$	is the $k^{th}$ predictor variable for producer $i$ in period $t$
$e_{it}$	is the error term for producer $i$ in period $t$

The simplest model is the linear model in Equation 6. The NASA model uses the multiplicative model for the market share estimation which is represented in Equation 7. The problem with the linear and multiplicative models is that these types of models do not guarantee the two fundamental aspects of the market share concept. First, the range of any market share is limited to the range  $[0,1]$ . Second, the sum of the market shares of all producers must be equal to 1. The third type represented in Equation 8 guarantees the logical consistency. A modified version of this type has been applied to the commercial aircraft market[81]. The high  $R^2$ -value attributed to their model is enabled by the incorporation of a general auto-regressive distributed lag (ADL) framework that is also used in several other market share studies [60, 159]. The benefit of ADL is the consideration of auto-correlation by implementing the lag effects of the predictor variables on the resulting market share.

$$\ln S_{US,t}^* = \alpha_{US}^* + \sum_{k=1}^K \beta_k X_{kit}^* + \ln S_{US,t-1}^* + \lambda T + e_{US,t}^* \quad (9)$$

where

$$\begin{aligned} \ln S_{US,t}^* &= 0.5 \ln \left( \frac{S_{US,t}}{1-S_{US,t}} \right) \\ S_{US,t}^* &= \frac{S_{US,t}}{S_t} \\ \alpha_{US}^* &= \alpha_{US} - \alpha \\ e_{US,t}^* &= \ln \left( \frac{e_{US,t}}{e_t} \right) \end{aligned}$$

$S_t$	is the geometric mean of $S_{it} \forall i$
$\alpha$	is the arithmetic mean of $\alpha_i \forall i$
$e_t$	is the geometric mean of $e_i \forall i$
$\lambda$	is the coefficient for the time trend
$T$	is the index for time

Although this type of model is hard to calibrate and compute in some occasions, it satisfies the logical consistency when there are two producers such as an American and European duopolists and reaches very high R squared ( $R^2$ ) values. Also known as coefficient of determination, these values indicate how well data fit a statistical model. The model developed by Fernandez reach values in the range of 58-75% [81]. The previous models reached values in the range of 13-61% and the NASA model has reached 47%.

The need for using such an empirical model comes from two main reasons. First, the factors that influence the airline's aircraft decisions should be identified. Second, the impact of these factors on the final decision should be quantified. The authors have identified the following factors to be statistically significant in the analysis:

- **The market region:**
  - The United States
  - Europe
  - Asia-Pacific
  - Rest of the World (mainly South America, Africa and the Middle East)
- **Main elements of lifecycle cost (LCC) from the airlines point of view:**
  - Acquisition cost
  - Fuel efficiency
- **Exterior factors:**

- Fuel prices
- Dollar's value vs. Euro (\$-€)

The demand models such as these have other benefits. One significant contribution of this model is the indirect capability of converting a potential multi-objective decision making problem into a single-objective one. Such example is the MDO of an airliner. Manufacturers constantly conduct tradeoff analysis between many design objectives. The acquisition cost vs fuel efficiency is an important one as these two objectives lead to significantly different designs as shown in Figure 9 [109]. In addition to the list, it is also possible to argue the maintenance cost to be an important factor for the LCC from the airlines point of view. A higher aspect ratio wing that minimizes the fuel burn is also more expensive to build and may lead to higher unit prices. When such a market share model is used, market share as a single metric becomes a representation of all these tradeoffs that may help in finding “sweet spots”. This is a critical enabler to value-driven aircraft family design.

#### 4.1.1.1 Simplified Demand Functions

Using a complex empirical market share model, such as the one described in Equation 9, is often impractical to use for theoretical derivations, and numerical simulations. When the simulation of a multi-firm, multi-product market is considered, the problem may quickly become a hard-to-handle computational burden. For the static case of two two-product firms **A**, and **B**, profit function for firm **A** can be defined as:

$$\Pi_{p_1^A, p_2^A}^A = p_1^A * q_1^A(p_1^A, p_2^A, p_1^B, p_2^B) + p_2^A * q_2^A(p_1^A, p_2^A, p_1^B, p_2^B) - C^A(q_1^A, q_2^A) \quad (10)$$

where the strategic control variable of the competition is price  $p$  with the assumption of a Bertrand competition. Quantity,  $q$ , is a function of prices, and can simply be written as

$$q_1^A = M * S_1^A(p_1^A, p_2^A, p_1^B, p_2^B)$$

so that the quantity output of firm **A** in segment **1**,  $q_1^A$ , is a function of the total market demand for both segments **1**, and **2**,  $M$ , and the market share of firm **A** in segment **1**,  $S_1^A$ , which is a function of the price decisions of both firms, in both segments, such that

$p_1^A$  is the pricing decision of firm  $A$  in segment  $1$ . Since the quantities in this case are functions of all the pricing decisions by all firms, and in all segments, such an approach allows the demand shift between segments which is explained by cross-price elasticity in the next section. However, for the application in this thesis, the price competition may not be the most advantageous selection. First, cost,  $C$  is always a function of the quantities, not the price so it is more straightforward to calculate the total cost when the quantity is directly the strategic control variable. The real burden of a price constraint is mainly in the simulation of capacity constraints. When quantity is a function of the price, as in Equation 9 and 10, the numerical simulation requires an additional step to check if the quantity output is within the capacity allowances.

Literature on the way competition occurs in the LCA industry is divided, and there is no clear, widely accepted standard of the way the competition occurs [114][103]. In fact, Irwin and Pavcnik have come up with very similar markup margins when they modeled the competition in both ways. Equation 10 can be rewritten in the Cournot competition form:

$$\Pi_{q_1^A, q_2^A}^A = q_1^A * p_1^A(q_1^A, q_2^A, q_1^B, q_2^B) + q_2^A * p_2^A(q_1^A, q_2^A, q_1^B, q_2^B) - C^A(q_1^A, q_2^A) \quad (11)$$

with the capacity constraints:

$$q_1^A + q_2^A \leq Q_{max}^A$$

where  $Q_{max}^A$  is the production capacity of the firm  $A$  with the assumption that the production of the product for segment  $1$ , and segment  $2$  are equally difficult, imposing a substitutable upper bound to both production quantities.

Examples given in Equation 9 and 10 are for single-period, myopic, and deterministic profit maximization problems. In order to expand this example to a multi-period, long-run, and stochastic profit maximization problem, first a profit function is defined for a specific time epoch, firm, and segment:

$$\pi_{ijt}(i, s_t, q_{ijt}, M_{jt}) = p_{ijt}(i, s_t, q_{jt}, M_{jt}) * q_{ijt} - c_{ijt}(i, s_t, q_{ijt}) \quad (12)$$

where



$\pi_{ijt}$	is the profit of firm $i$ in segment $j$ at time $t$
$p_{ijt}$	is the price of the vehicle designed for segment $j$ by firm $i$ at time $t$
$q_{ijt}$	is the quantity produced for segment $j$ by firm $i$ at time $t$
$c_{ijt}$	is the cost of the vehicle designed for segment $j$ by firm $i$ at time $t$
$j$	is the segment
$i$	is the firm
$t$	is the decision epoch
$s$	is the industry structure that includes the states of all the firms
$M_{jt}$	is the overall demand for the market segment $j$ at time $t$

In this form, the state of the industry,  $s$ , is composed of the market presence of the other competitors, and their production quantity decisions, as well as their designs. To obtain the price function  $p_{ijt}$ , a simple utility function should be obtained. Utility functions of linear forms are faster to use in iterative computations, compared to models of Equation 7 and Equation 8. There are multiple ways of creating market share information from utility functions such as multinomial logit models. Those types of models can also enable simulation of oligopoly cases, instead of duopolies.

#### 4.1.2 Product Substitutability and Cross Price Elasticity

As mentioned in Chapter 3, especially in the narrow-body market, the design missions for the variants within a family are relatively close compared to the wide-body market therefore implying a potential “substitutability” between the products. In such circumstances, an airliner may acquire other aircraft than the “preferred” models. In fact, the price sensitivity mentioned with the model described in Section 4.1.1 can be considered as the own-price elasticity of demand given the practices of the other manufacturers. Generalized price elasticities in this case are three types:

$$\eta_{j,j} = \frac{\partial s_j}{\partial p_j} \frac{p_j}{s_j}$$

$$\eta_{j,k} = \frac{\partial s_j}{\partial p_k} \frac{p_k}{s_j} \text{ if } j \neq k, k \in g, j \in g$$

$$\eta_{j,k} = \frac{\partial s_j}{\partial p_k} \frac{p_k}{s_j} \text{ if } j \neq k, k \notin g, j \in g$$

where:

$\eta_{j,k}$  is the price elasticity of demand between products  $j,k$

$p_k$  is the price of the product  $k$

$s_k$  is the demand for the product  $k$

$g$  is the market segment  $g$

The first type is also known as the own-price elasticity of demand. It is used to measure how a price of a product changes when its own price is increased. In the second type, two different products that are in the same market segment are considered. This is also called cross-price elasticity within the same segment. Finally, in the third type, two different products in two different markets are considered which is also called the cross-price elasticity across segments. Irwin has collected data from various narrow-body and wide-body aircraft transactions from 1969 to 1998 to come up with the numbers presented in Table 7 [103]. A positive cross-price elasticity indicates substitutability between vehicles. Considering the fact that authors conducted this study by grouping the market into two groups, a very low value between wide and narrow body segments suggests that these two goods are practically independent. An airliner looking for a wide-body addition to their fleet will not be likely to go for an attractive narrow-body aircraft pricing. However, the significant values of cross-price elasticity within the segments suggest that a competition is fierce within the products of the same segment as they are substitutable. Another interesting conclusion from this data is the significant increase in the magnitude of the own-price elasticity throughout the years suggesting the competition has become stronger.

It is a known fact that products in the product families of today do not only compete with individual or family products of the competitors but also with other products that belong to the same company and sometimes the same family. With that observation in mind, the substitutability between vehicles, especially in the same segment creates new market

Table 7: Price Elasticities within Different Periods [103]

Period	Own Price	Cross-price within same segment	Cross-price across segments
1969-1973	-2.901	2.570	0.502
1974-1978	-3.750	1.604	0.098
1979-1983	-4.079	1.858	0.101
1984-1988	-4.822	1.789	0.047
1989-1993	-6.410	2.007	0.071
1994-1998	-7.813	1.436	0.047

opportunities. Recalling the concepts of ideas from Figure 6, COMAC's strategy with COMAC C919 in the narrow-body segment may be depending on shifting some of the demand from the other subsegments by offering a highly competitive product in just a single subsegment. Since it is planned to compete with B737MAX8 and A320neo which is a very popular subsegment, this strategy of introducing a single product for competing against a family of products needs extra attention. It is an intermediate size aircraft that is capable of "stealing" demand from both the larger and the smaller subsegments.

#### 4.1.3 Family-specific Cost Benefits and Modeling

The methods of quantification of the economical impact of a program is essential to the cause of this research and proper ways to assess the magnitude of cost of different vehicles and strategies is critical. The major elements of cost in an aircraft program lifecycle are the initial non-recurring investment (R&D cost) and the recurring costs (production cost). Using a common platform among different aircraft have different benefits that shape the cost structure in these two elements. Fujita et al., in an attempt to quantify the cost benefits, divides the cost into three elements: design and development cost, facility cost, and production cost [89]. Similar to the development cost, facility cost is also a non-recurring, one-time cost element. Unlike the development cost however, in their cost model, facility cost is a function of the aircraft dimensions whereas the development cost is a function of the weight. There are several problems with cost modeling due to lack of data revealed by the manufacturers. Based on the literature review, several findings, as candidates of realistically modeling an aircraft family design, are presented here.

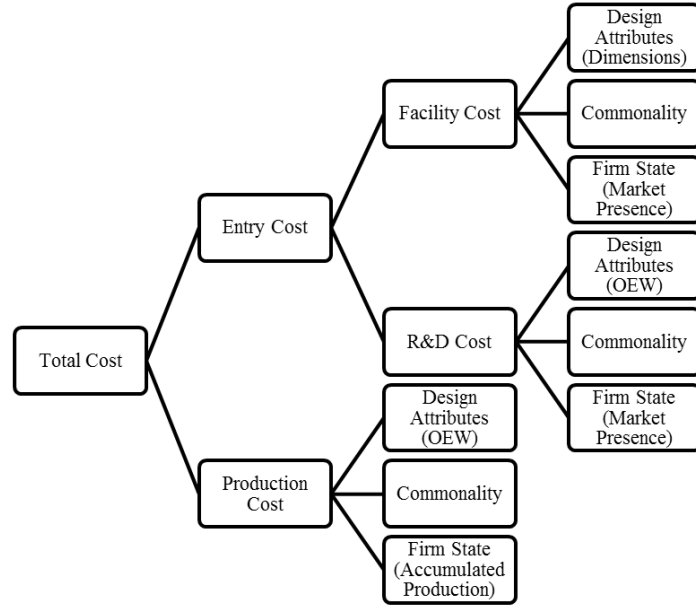


Figure 29: Cost Components and Dependence Breakdown

#### 4.1.3.1 Research and Development Cost

R&D cost, occasionally known as the Research, Development, Testing and Evaluation (RDT&E) cost, includes all the technology research, design engineering, prototype fabrication, flight and ground testing, and evaluations for operational suitability [169]. It is usually a fair assumption to consider R&D effort to be independent of the number of units to be produced. RAND DAPCA IV cost model is the most widely accepted publicly available model for estimating the R&D cost [97]. Such an empirical model is needed to have a starting point for assessing the viability of a business, but there are some drawbacks related to it. First, the model is mainly dependent on the empty weight of the design which may not represent some of the practices conducted in the industry today, such as additions of new technologies. For example, a revolutionary material technology may be costly, but reduce the empty weight of the airplane to result in fuel savings. Second, the result is a deterministic value, which in reality is haunted by different sources of uncertainty. Third, the model doesn't account for the reduced R&D cost resulting from the development of a derivative from a baseline. The last factor in particular leads to the need for various assumptions

Table 8: Commonality Cost Reduction Factors [105]

Cost Contributor	$f_k$
Engineering	0.60
Labor	0.80
Materials	0.95
Quality Control	0.80
Support	0.80
Tooling	0.50

to be made to account for. Weight based analysis are common for assessing the commonality benefits at the R&D level [133, 90, 104]. These approaches resemble the traditional commonality index based approach used by product family design community. There are various types of commonality indices in literature [191]. In simple terms, a commonality index is “a metric to assess the degree of commonality within a family”. The weight based example is presented here on the guidelines of Perez et al. [104]:

$$CI_j = W_{common} / (W_{common} + W_{exclusive})$$

$$C_{jk}^* = f_k C_{jk} \frac{1}{CI_j}$$

where

$W_{common}$  is the weight of common modules

$W_{exclusive}$  is the weight of exclusive(unique) modules

$CI_j$  is the commonality index for the part j

$C_{jk}$  is the value of the kth cost contributor for a baseline

$C_{jk}^*$  is the value of the kth cost contributor for a derivative

$f_k$  is the commonality cost reduction factor

In the absence of detailed derivative cost data, many authors have come up with approximations to how much the commonality benefits the cost elements. Intuitively, commonality’s main strength is in reduced engineering hours and tooling cost as they are shared among common derivatives in particular. With a similar reasoning, the material requirement would not get greatly affected although some efficiency improvement can be expected

through reduced wastage. Fujita expands the module based R&D cost estimation with a weight-based approach, and intuitive coefficients [88]. Specific application they propose to model the “stretched fuselage” benefits requires an explicit representation of such modules that are not same, but very similar.

$$C_D^i = \sum_{j=1}^m C_{D_j}^i$$

$$C_{D_j}^i = \begin{cases} \alpha_{D_j} W_j^i & \text{for independent design} \\ \left( \beta_{D_j} \frac{W_j^i - W_j^1}{W_j^1} + \gamma_{D_j} \right) C_{D_j}^1 & \text{for similar design} \\ 0 & \text{for same design} \end{cases}$$

where  $C_D^i$ , the design, and development cost for product  $i$ , is composed of the individual development costs for  $m$  number of modules,  $C_{D_j}^i$ . The coefficients used,  $\alpha_{D_j}$ ,  $\beta_{D_j}$ ,  $\gamma_{D_j}$ , are in the form of [currency/weight], and [yen/kg], in the original example. Weight differences between modules,  $W_j^i - W_j^1$ , are used to estimate the development cost of the derivative module of similar designs. The analogy from this weight-based methodology will be assumed for the work in this thesis. Section 5.3 details the approach used in this methodology.

#### 4.1.3.2 Production Cost

Production cost is the umbrella term for all the recurring costs in an aircraft program. In its simplified form, it consists of two fundamental elements: material cost and labor cost. From the production of a product family point of view, the actual benefits are not in the material cost reductions, but the labor cost. This is mainly due to the learning curve effect, which was explained in Section 3.5. To estimate, and signify the learning curve effects in product families, here a module based labor cost breakdown is shown here. Recalling Equation 4, the module based labor requirement for a family is defined in a similar fashion to the works of Fujita, and Jansen [88, 104]. Also, the relationship between weight, and the cost is linearized similarly to the work of Markish et al. [134]. This is not the case observed in the RAND DAPCA IV model, which proposes power relationship between the OEW and the costs [97]. However, it is an acceptable assumption to choose a baseline vehicle, and linearize the cost equation around that specific design.

$$C_P^i(\ell^i) = c_m^i + c_p^i(\ell^i)$$

where the production cost of for the  $\ell$ -th unit of the product  $i$ ,  $C^i_P(\ell^i)$  is composed of the material cost,  $c_m^i$ , and labor cost,  $c_p^i(\ell^i)$ . cmi is given as:

$$c_m^i = \sum_{j=1}^m V_j W_j^i$$

where the material cost,  $c_m^i$ , is a function of the weight of the module  $j$  of product  $i$ ,  $W_j^i$ , and a material cost per weight coefficient  $V_j$  for the module  $j$ .

$$c_p^i(\ell^i) = \sum_{j=1}^m K_j W_j^i u(\ell_j^i)$$

where the family-wide production labor cost reduction coefficient for the product  $i$ , and module  $j$ ,  $u(\ell_j^i)$ , is:

$$u(\ell_j^i) = \left( \ell_j^i + \sum_{I=1, I \neq j}^p R_{jI,i} \ell_j^I \right)^{\frac{\ln r}{\ln 2}}$$

where  $K_j$ ,  $R_{jI,i}$  are coefficients for module slots, and learning coefficient from similar designs respectively.

Quantification of cost benefits of commonality is paramount to any product family design effort that aims to maximize the program value. However, just as in case of market demand modeling, such supporting cost models are usually empirical. Since companies do not reveal their firm-specific data, such models are very hard to calibrate.

#### 4.1.4 Market-Oriented Product Design

One of the realities of today's market-oriented design is the marketing executives' constant desire to explore and utilize new market gaps and opportunities which usually conflicts with the constraints imposed on the design engineers. To address this problem, there have been various attempts with one common perspective. If the design decisions have market consequences, the connections between the revenue, cost and corresponding design characteristics should be quantified. Also, it is known that the commonality as a tool in the design of product families is related to all three of these elements. First, the existing literature on the individual product design for market systems is reviewed. In Section 4.1.5, the limited literature on the product family design for competitive markets is presented. The main motivation for any of these studies is the understanding that the engineering decisions will affect economic decisions through the product lifecycle whether it is a single product or a multi-product line. In an attempt to avoid documenting the vast variety of

market-oriented product designs that do not consider family positioning, this section only generalizes those approaches. It is possible to group product design problems that take competitiveness into account in two groups:

- **Short-run Price Equilibrium:** Design attributes of all the competitor products are fixed in the beginning and only the prices will be adjusted to reach the equilibrium. Short-run equilibrium can also be in quantities instead of prices.
- **Long-run Design Equilibrium:** Competition is sufficiently long-term that the competitors have enough time to both readjust the design attributes as well as the prices.

In simple terms, the Nash Equilibrium (NE) for a short-run Nash competition, new product design variables, new product price, and competitors' prices, there are three sets of simultaneous equations [179]:

$$\frac{\partial \Pi_k}{\partial x_j} = 0; \frac{\partial \Pi_k}{\partial p_j} = 0; \frac{\partial \Pi_{k'}}{\partial p_{j'}} = 0$$

where  $\Pi_k$  is the net profit of all new products  $J_k$  from producer  $k$ , and  $\Pi_{k'}$  is the net profit sum of the products of competitor  $k'$ . In this example,  $\mathbf{x}_j$  is the vector of design variables of product  $j$ , and  $\mathbf{p}_j$  is the price of the same product.  $\mathbf{p}_{j'}$  is the price of competitor's product  $j'$ . In simple terms, profit can be expressed as:

$$\Pi_k = \sum_{j \in J_k} (p_j - c_j) q_j \quad \Pi_{k'} = \sum_{j \in J_{k'}} q_{j'} (p_{j'} - c_{j'})$$

where, for product  $j$ ,  $\mathbf{p}_j$  and  $\mathbf{c}_j$  are the price and cost of the corresponding product respectively.  $s_j$  denotes the market share of product  $j$ , which is a function of design attributes  $\mathbf{z}_j$ , price  $\mathbf{p}_j$ , competitor design attributes  $\mathbf{z}_{j'}$ , and competitor's price  $\mathbf{p}_{j'}$ . Multiplication of the market share with the overall market demand  $Q$  gives the market demand for the product  $j$ :  $q_j$ . Cost  $\mathbf{c}_j$  is a function of design attributes as well as the quantity. Similarly, design attributes  $\mathbf{z}_j$  is a function of design variables  $\mathbf{x}_j$ .

$$q_j = Q s_j, \quad s_j = f_s(p_j, z_j, p_{j'}, z_{j'}), \quad z_j = f_z(x_j), \quad c_j = f_c(x_j, q_j)$$

Although this example approach is static and simplified, it provides a logical baseline to build on for the design-for-market approaches, especially for Class III models. For most engineering applications though, these profit considerations should be evaluated subject to engineering constraints. Another possible way of classifying the existing market-oriented



product design literature is based on how the competitor reactions are modeled [180]:

- **Class I:** Perspective of a single firm is considered where there are no other decision makers, or competitive reactions. This approach is the most simple and popular technique, and in certain cases, it can be compared to a monopolistic approach. Consumers have two options: purchase the product from the single firm, or not purchase at all. In fact, the single firm competes against an outside good in Class I literature. Models that doesn't account for competitor reactions tend to overestimate the profitability of firms [179].
- **Class II:** Competitor designs are not fixed, but they may react by adjusting the price, or the quantity. These problems are usually solved by game-theoretic approaches [87]. These problems result in solutions in the form of equilibriums, which usually leads to the concept called Nash Equilibrium (NE). At the NE, no firm can make a decision to change price, or quantity without decreasing firm's payoff. Design can still be optimized for the static attributes. Short-term firm policies can usually be explained by Class II models.
- **Class III:** Firms can change both the prices, or quantities, and the design as a reaction to a new product entry. In such conditions, NE is located by solving the price, or quantity and design simultaneously. In certain cases, Class III problems can be formulated as an extension of the short-run price equilibriums [59]. These types of problems are the most difficult examples, and different methods have been proposed to find the equilibria [180, 144].

For decision-makers, all these three classes are in fact, single-stage equilibria where any producer is forced to make all decisions simultaneously. When IO applications are considered, these single-stage approaches are very simplified concepts. For IO purposes, the alternative is a Subgame Perfect Equilibrium (SPE) where manufacturers can make a design decision, but most of the time the decisions are made on prices, or quantities [192].

Decision-Based Design (DBD) is another framework that focuses on designing the most valuable product [95]. Focus of that framework is to identify the design alternatives that

can maximize the value of the product. Within that context, profit is a bottom-line measurement of value [112]. Optimization techniques include analytical target cascading, and collaborative optimization [143][170]. Despite considerable amount of research being focused on product design under competition, the studies on competitive product family design problems are limited. Next section surveys the existing literature.

#### *4.1.4.1 Value-Driven Aircraft Design*

The trend in engineering design of vehicles for market systems is shifting from cost control to value creation and existing mechanisms are populated by costing approaches rather than value approaches [106]. The same VDD approach for commercial aircraft is explained in Section 2.7. There are other notable works in the domains of VDD aircraft design.

Peoples realizes that a stochastic value-based optimization can result in a 2.3% higher program value than the traditional weight-minimizing solutions for a case study on a Blended Wing-Body (BWB) [162]. The realization of the importance of managing long-term cash flows over focusing solely on the development costs have enabled the idea of combining elements of vehicle performance and managerial flexibility with uncertainty. Markish uses DP enhanced with cost, and revenue tools to account for future uncertainty in an aircraft program [132]. However his approach assumes no competitive reactions.

#### *4.1.4.2 Market-Oriented Product Family Design*

More and more product family design problems have started incorporating customer-driven approaches rather than pure performance and cost-driven engineering approaches. Kumar et al. utilize demand modeling for product line positioning as they investigate different market niches [124, 125]. They clarify the need for simultaneous consideration of performance, cost, and marketing decisions in product family design literature. Lou shows that such concurrent approaches combining the elements of engineering, and marketing results in more profitable product families than alternate approaches [131]. Michalek et al. find that the correct number of products may not be equal to the number of market segments for maximizing firm-level profits as they differentiate between homogeneous and heterogeneous market systems [143]. They conduct their experiments using a Bayesian account of consumer

preference heterogeneity.

Market focus is not always easy to assess on its own. Cost and customer perceptions become important elements of such studies. Jiao et al. point the importance of cost modeling across products as economies of scale and scope affect family products in different ways [107].

Li and Azarm presents an approach that solves a product line selection problem using GA [128, 129]. NPV of total profits and the market share are their main goals. The competition in their approach is known and fixed as they do not consider the potential competitive reactions. The work of Heese and Swaminathan solves a problem in which the manufacturer sets the price and quality levels of two products offered in two market segments in a setting that doesn't include competitor reactions [96]. Farrell et al. consider a problem that a manufacturer tries to find the optimal product platform in a cost-focused approach [80]. Ramdas et al. attempt to find the optimal choice of adding a new product to an existing product family with revenue and LCC implications [168].

#### **4.1.5 Competitive and Flexible Product Family Design**

Although all market-driven approaches, whether a single product or a product line, passively or actively incorporate competitive reactions, in this section the main focus is the product family design literature in which the competitors react often by rival product families. Limited literature on the design of flexible family design approaches will also be presented.

Li and Azarm present some of the key papers in the area that is specific to aircraft design [128, 129]. However, their approach is enabled by several assumptions. First of all, in their case, there is no product by the company in the market before the launching of a product line. Second of their assumptions is that the customers definitely choose a product with the highest utility, as they use a first choice utility model. Third assumption, which accompanies the second, is that the customers' preferences remain unchanged during a product's lifecycle. The methodology proposed here builds loosely on similar assumptions.

The methodology proposed by Li and Azarm has some other assumptions that simplify the problem but ignore some of the key elements of the way competition occurs. In their

approach, market competition is present and static as there is no reaction from the competition after the launching of the new product line. Instead of this assumption, this thesis proposes a methodology that can take this into account, and identify a market equilibrium in the presence of competition. They also assume that all variants in a product line are launched into the market at the same time, which was rejected by the Observation 9 as shown in Figure 24. As previously explained, most of the time, even though the manufacturers have all the products in mind when the platform is being designed, models are introduced at different time intervals. This problem also requires strategic decision making at the managerial level. Another assumption they make is that all the variants in a product line have a lifecycle of the same duration. This framework limits the simulation duration into a finite amount of years, which in the end no product by any firm is present in the market. Since it is possible that some products will be introduced later than the others, and a finite duration is defined as an outside parameter to the simulation, some products will stay in the market for longer. Entrants will have less time in the market because of late entry. It is possible to argue that their approach, which doesn't take competitive reactions into account, may result in sub-optimal designs.

Suh proposes a formal methodology for “Flexible Product Platform Design” in following steps [188, 189]:

1. Identify markets, variants, and uncertainties
2. Determine uncertainty related key attributes and design variables
3. Optimize product family and platform bandwidth
4. Identify critical platform elements
5. Create flexible design alternatives
6. Determine costs of design alternatives
7. Uncertainty analysis

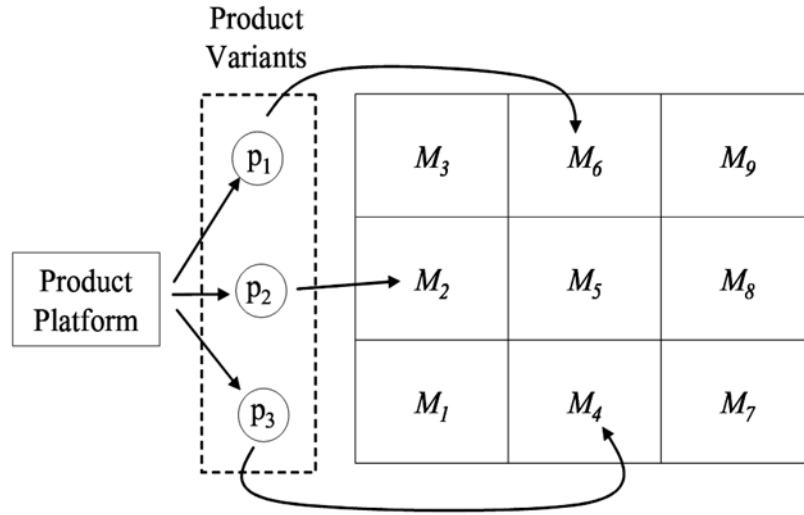


Figure 30: Implementing Product Platform to Different Segments [66]

Suh's steps are important to the understanding of flexibility among product families, that is to enter the market, or not, even though the common platform is established. This thesis follows a similar approach with the addition of competition to his approach.

Sichani comes up with a pure competitive analysis of product families [112]. The methodology developed is initially applied to a single product with the focus on maximizing the profitability under competition. Then, the author expands the application into product families. The way the uncertainty is handled is through different case studies in which different parameters lead to different deterministic results.

Another notable work is that of Kalligeros et al. in which the authors use real options to value flexibility [111]. They use a two-step methodology for valuing this flexibility enabled by various standardization strategies for future developments in a program of projects.

#### 4.1.6 Ericson Pakes Class Industrial Organization Models

Ericson and Pakes (EP) presents a general, dynamic, and strategic oligopoly model [76]. The model is based on a framework in which the firms can decide on many policies such as market entry/exit, and R&D investment, as well as other strategic control variables as real options. The framework, which is a dynamic, stochastic game with a discrete state/action space, works with a set of input primitives that describes the structure of the industry.

The output is a set of policies, and resulting profits for all the incumbents, and potential entrants at each time period.

Essentially, the EP framework gives up on analytical considerations for the sake of numerical simulations. However, since firm heterogeneity is considered with both firm and industry specific variability, the advantages of these numerical simulations is that the industry payoffs can be quite different in each simulation even for similar firms.

Doraszelski et al., about the capabilities of EP models, states that “*The firm specific uncertainty is needed to account for the fact that we often see both simultaneous entry and exit and rank reversals in the fortunes of firms within a market (no matter how we define “fortunes”). The market (and/or) industry specific uncertainty is needed to rationalize the fact that often the firms competing in a given market (or industry) are subject to changes in costs or demand conditions which cause their profits to be positively correlated.*” [71]. This nature of the EP models makes it a highly suitable candidate for the application in this thesis.

According to Adamodar, multi-stage investment models should be preferred over one-time investment models in these cases [65]:

1. Projects that have significant barriers to entry from competitors entering the market.
2. Projects that have significant uncertainty about the size of the market and the eventual success of the project
3. Projects where there is a substantial investment needed in infrastructure, such as high R&D costs

LCA market is a good candidate that matches these criteria due to the observations listed in Chapter 3. From the market entry/exit perspective, EP model is a very valuable tool since it is powered by dynamics such as an entrepreneur exploring a perceived profit opportunity, or an existing enterprise that only perceives a future loss and eventually decides to exit the market completely.

EP framework relies heavily on empirical estimation models, but with the proper structural estimations, it can be used to model & simulate a large variety of industries to obtain

Table 9: Applications of EP's Framework [71]

Application Area	Example Paper
Advertising	Doraszelski and Markovich(2006)
Capacity Accumulation	Besanko and Doraszelski (2004)
Collusion	Fershtman and Pakes(2000, 2005)
Competitive Convergence	Langohr(2003)
Consumer Learning	Ching(2003)
Firm Size and Growth	Laincz and Rodrigues(2004)
Learning-by-doing	Benkard(2004)
Mergers	Berry and Pakes(1993)
Network Effects	Jenkins et al.(2004)
Productivity Growth	Laincz(2005)
R&D	Gowrisankaran and Town(1997)
Technology Adoption	Schivardi and Schneider(2005)
International Trade	Erdem and Tybout(2003)
Finance	Goettler, Parlour and Rajan(2005)

an equilibrium. The theory of MPE is defined in several sources [69][192, 137]. Among the applications of EP framework, it is also not uncommon to see MCS implementations [150].

## 4.2 The Framework

### 4.2.1 Research Gap

Product family and platform design requires detailed consideration of the market dynamics. The common performance considerations for family design must be coupled with the consumer preferences, market uncertainty, and competitor reactions in a dynamic environment. Despite all research efforts directed towards designing product families for different purposes, two elements have not attracted sufficient interest [182]:

- Integration of Management and Engineering Aspects
- Consideration of Dynamic Issues

In the product family literature, which received significant contributions in the last two decades, there is a visible need for more studies to consider the effect of market demand, and the product design. Some of that literature is already presented with examples [128, 129, 90, 88, 124, 125, 142, 143].

The second hot topic in product family literature is the consideration of dynamic issues. The word “dynamic” has been used for two different meanings in this proposal document. One definition implies the time dependency, whereas the other definition is used for entities that react to each other. Zacharias et al. have identified the system uncertainties as dynamic elements that should actively influence the design decisions [203]. Shiao et al. have worked on the competitor reactions in a market environment [180, 179]. Michalek et al. have performed the critical step of expanding these considerations to a product line level from a single product design [142]. There are also other types of research addressing dynamic issues such as the work of Fixson in which the authors focus on supply chain related issues [84].

Product family optimization problems can become complex very fast, especially when the uncertainty, competitor reactions, and marketing-engineering-manufacturing considerations are integrated. In the field of product family design, there have been some attempts at identifying the global optimality [116, 117]. These attempts at improving the design space exploration are essential for such complex problems.

Initially, commonality has been identified as an important tool in increasing the program values. Then, the observation of the industry has shown the existence of certain elements that should be incorporated into any design method in question. These are uncertainty (both market-wide and idiosyncratic), competitor reactions (both in derivatives and pricing/quantity), dynamic elements, market entry/exit, and flexible managerial decisions. A framework is needed to address all these issues simultaneously while addressing some of the overall needs of the product family literature. The hypothesis is formed as a response to the primary research question. So far in the literature, a framework to address such critical elements simultaneously has not been identified and stand-alone approaches of game theory and real options fail to do so. Following the conclusion to the secondary research question, a hypothesis is created to answer the primary research question. The literature review summarized in previous sections indicate that EP class IO models are well suited considering the market observations due to their capability to model dynamic industries with heterogeneous firms. In fact, Benkard has demonstrated the capabilities specifically



Table 10: Research Gap

Element	Sub[189]	Li[129]	Gonzalez[93]	Fujita[90]	Michalek[142]	Markish[134]	Willcox[200]	Peoples[162]	Sichian[112]	Zacharias[203]
Endogenous Uncertainty	✓	✓	✓					✓		✓
Exogenous Uncertainty	✓	✓	✓	✓		✓		✓		✓
Competitor Reactions (Design)					✓				✓	
Competitor Reactions (Pricing)					✓				✓	
Family Considerations	✓	✓	✓	✓	✓	✓	✓		✓	✓
Multi-Stage	✓	✓	✓			✓	✓	✓		✓
Market Entry/Exit										
Flexibility	✓		✓			✓		✓		✓

for the aircraft industry [42, 43].

**Research Question 1:** *For a given oligopolistic market system with inherent uncertainty, how can an aircraft manufacturer estimate the expected family program value? How can we use this valuation technique to assess program risk of a new design?*

To conclude the literature review, an overarching hypothesis is formed. EP models are found to be applicable to the specific problem in this thesis.

**Hypothesis:** *Considering the dynamic, stochastic, competitive, and flexible nature of aircraft family programs, combining an Ericson Pakes class Industrial Organization model of dynamic oligopoly with Monte Carlo Simulations enables the designer to make risk-informed, value-driven platform design decisions in the conceptual design phase.*

## 4.2.2 Framework

### 4.2.2.1 Major Assumptions

Modeling and simulating a competition to identify valuable designs is a difficult task. Any research attempt addressing this area needs clear assumptions. First, assumptions related to firm's behavior is explained. Aircraft manufacturers as players have the following characteristics:

- **Firms play strategically with long-term goals:** Instead of myopic, short-term profits, the firms focus on the overall goals for the entire program lifecycle.
- **Firms (both incumbents, and entrants) have similar expectations of uncertainty:** Although firms may be subject to different idiosyncratic shocks, they have similar expectations of market-wide uncertainty such as demand fluctuations, and fuel prices. No firm has the perfect information, or complete confidence about the future. They all observe the same forecast, with the same confidence interval.
- **Firms do not enter the market if an economic return is not anticipated:** This assumption is critical to limit the number of firms to a finite value, as market can only sustain a certain amount of players. This assumption is also easy to justify from a realistic perspective as firm theory suggests that the firms exist to generate value.

- **Firms are value-maximizers:** Firms will follow the policies that result in a maximized value metric. Value metric in this case is the NPV.
- **Firms act rationally:** Firms behave according to rational expectations.

It is possible to argue that these assumptions do not differ significantly from the actual motivations of existing firms, though one critical aspect about these assumptions is the reality of the incumbent firms, to possibly deter new entrants at all costs. In this thesis environment, incumbent firms will do anything to maximize their program values. Most of the time, it is logical to expect these firms to try to prevent the new entry at the expense of short-term benefits.

Once the motivations of the firms, which are players(or agents), are defined, the second step is to define the structure of the market. In this framework, firms compete in prices (Bertrand competition), instead of quantity and the price is chosen as the control variable. The literature is divided between whether the aircraft manufacturers compete in price, or quantities, therefore any preference is acceptable. Also, choosing price as a control variable will allow an easier interpretation of the values and is more intuitive. One drawback of such an approach though is that the direct mathematical implementation of the capacity constraints is no longer possible. In this system, the framework doesn't allow the simulation of backlogs, and all the deliveries are immediate. If a certain amount of vehicles are demanded, and the amount is within the production limitations of the firm, then the delivery is made within the same year as the demand. Also, the revenue for the production is collected in the same time period with the demand, and the production. This assumption can be justified by the fact that many aircraft manufacturers will not be likely to produce "white-tails" without a guaranteed, fast payment.

Several authors such as Irwin and Pavcnik have analyzed the interactions between narrow-body, and wide-body markets [103]. Some of these results are shown in Table 7. Although significantly getting weaker within each time period analyzed, there is some price elasticity relation between these two markets. Within this work, wide-body aircraft are considered to be outside-goods, and any sort of relationship is neglected. A similar

assumption is also valid for the Regional Jet (RJ) market.

Airlines usually prefer similar cockpits, and therefore same families, to ease the crew scheduling. This is hard to model due to lack of data to help understand how favorable the conditions become for airlines to make a certain aircraft more attractive than its competitors. In this thesis, this aspect, although recognized to be significant in the real life acquisition practices, is ignored. Similarly, long-term good relationships between airlines and manufacturers may result in more likelihood of continuing business together, this is also ignored in the case study.

Production capacity is fixed throughout the program lifecycle. Although the maximum number of units the firms can produce in a single year is hardwired into the model in the beginning, and can always be altered, firms don't have the option to spend additional resources, and expand the production capacity based on the expectation in an increase in the anticipated net program value. This type of problems is another area of literature called the capacity expansion, management problems.

When both supply and demand sides of such a complicated field is analyzed, some simplifications are essential. For example, Airbus sells airplanes in US Dollars but apart from some of the outsourced parts and materials most of the cost is incurred in Euros. On the other hand Boeing operates almost completely on US Dollars. Such a difference could mean Airbus could receive shock from the fluctuations in the exchange rates between Euro and USD. Delivery lead time can also be an important element for airlines looking to expand their fleets quickly. Such factors, even though important, are hard to model. In addition, from a conceptual designer perspective, the focus is on the controllable elements.

#### *4.2.2.2 Scope*

Before proceeding with the explanation of a methodology, the scope of this framework needs to be specified. For this purpose, the main benefits of commonality to be considered are shown on a commonality advantage chart in Figure 31 [54]. This framework is intended to directly handle elements in bold boxes and is not capable of modeling the elements in dashed boxes. Elements in regular boxes, such as deploying new technologies, are not considered

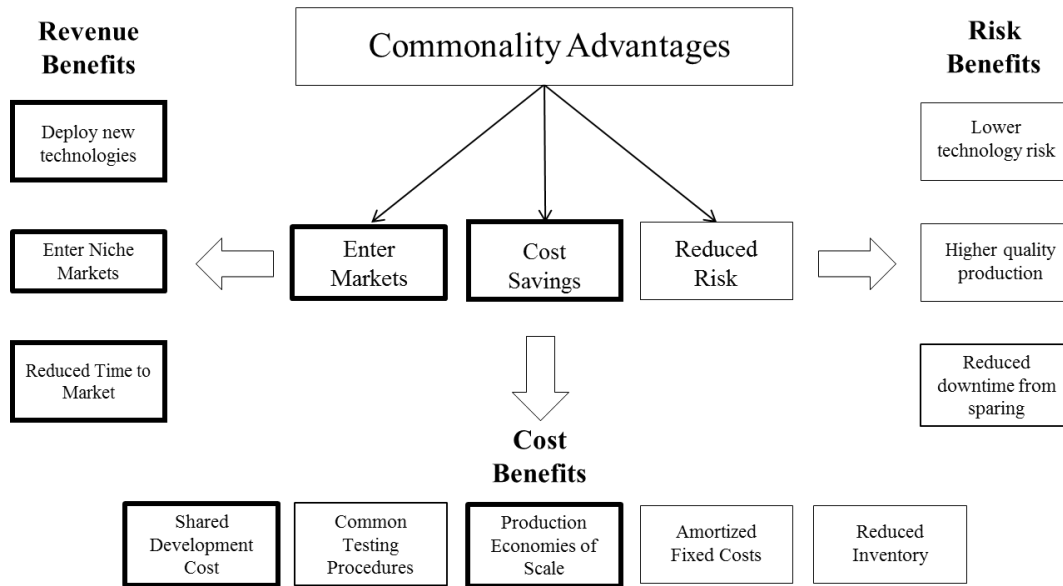


Figure 31: Main Benefits of Commonality [54]

by default, however they can be assessed with appropriate scenarios. The first part of this chapter was dedicated to demonstrate some marketing, and manufacturing specifics of common platform designs.

Second, the intent is to demonstrate the whole map of possible risks in a technology program. In Figure 32, there are four main types of risks: financial risks, strategic risks, operational risks, and hazard risks [31]. The focus in this framework is solely on addressing and minimizing the strategic risks. Both exogenous and endogenous factors are separately considered in the methodology. Among the elements of strategic risks:

- Competition (See Section 2.8)
- Customer Demand (See Section 4.1.1)
- Industry Changes (See Section 3.7.1)
- M&A Integration (See Section 3.1, not modeled)
- R&D (See Section 4.1.3 and Section 2.11.1)

have all been considered in this thesis proposal.

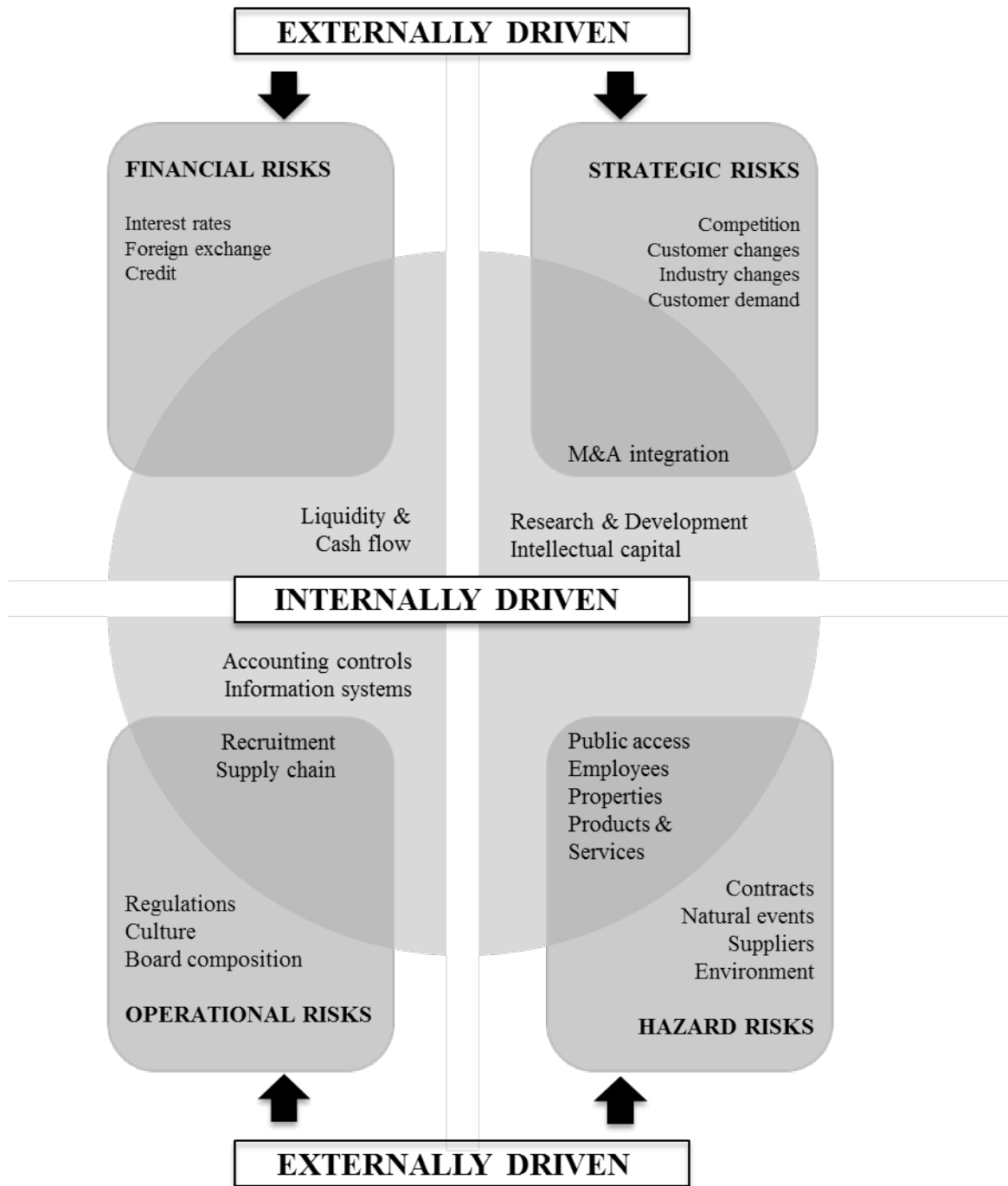


Figure 32: Risk Management Map [31]

As previously described, the competitive strength consists of three elements: differentiation, cost, and agility. In fact, these are the main elements of product family design, any designer must perform tradeoff studies on. Based on the presented observations, it is possible to argue that the most critical tradeoff in a family design effort is between the Observations 1,7,9 versus Observation 3. In the problem formulation, this tradeoff is particularly addressed. In this work, development of a new platform is not allowed (maximum one per firm), thus the strategy space is limited.

#### *4.2.2.3 Methodology*

To test the hypothesis and answer the primary research question, a competitive product family design methodology is introduced within this thesis framework. In the main stage, shown as Stage 5 in Figure 33, a multi-product, multi-firm dynamic market environment is simulated in which the players are the incumbent or new entrant aircraft manufacturers. The main motivation of these players is to maximize the family program value by making strategic and rational marketing decisions under uncertainty and competition. The stochastic game in that stage is modeled as a competitive Markov Decision Process (MDP) in which the players act non-cooperatively with the sole purpose of maximizing their own expected rewards. The players within the environment have the perfect information of each other's designs and prices. They also have the same knowledge about the uncertainty for an infinite time horizon. At each node, a rational decision is made after assessing the state of the market, actions of the competitors, future uncertainty, and some shock associated with internal and external firm dynamics. Cross elasticity of demand is also incorporated to the model in order to demonstrate strategies for smaller firms to possibly capture some of the demand from the other sub-segments the firm is not operating in. The second stage includes generating a family of candidate vehicles based on different scenarios.

Within this work, the LCA market is divided into narrow-body (single-aisle), and wide-body (twin-aisle) aircraft market segments. Classes of different aircraft sizes within each of these segments are further divided into sub-segments. Around the fore-mentioned first stage is a sizing and synthesis tool that is responsible for evaluating the common design variables

among the family members, estimating performance and cost responses for different scenarios. This second stage considers the first stage as a black box and only considers the common design variables as an input and the resulting program value as an output. For the scope of this thesis, the design decisions will be limited to the technology selection problem. For an infinite time-horizon game, the state transition matrices of the industry evolution can be obtained from the first stage analysis. Then, Monte Carlo Simulations (MCS) are conducted to obtain trends of Discounted Cash Flows (DCF) that can help create distributions of Net Present Value (NPV). In this case, MCS will provide useful insights to assess the risk. Since the firms actively react to different stochastic elements, same scenario can result in different market outcomes if the simulation is run multiple times.

Formally, the methodology proposed here is composed of:

#### **1. Create the Market Environment**

- (a) Market Segmentation
- (b) Market Uncertainty-Evolution of Demand
- (c) Demand Model

#### **2. Identify Players and Firm-specific Dynamics**

- (a) Incumbents (with observable designs)
- (b) Entrants (with changing designs)

#### **3. Identify Common Platforms**

- (a) Identify Critical Design Variables
- (b) Generate Candidate Family Platform Designs
- (c) Generate Performance and Cost Data for Candidate Family Members

#### **4. Market Simulations**

- (a) Industrial Organization



- (b) Monte Carlo Simulations
- (c) Obtain Distributions of Program Value

## 5. Platform Optimization

- (a) Pick value-maximizing platform design
  - i. One-step solution for one entrant
  - ii. Sequential Nash Equilibrium Solution for two or more entrants

In Figure 33, a novel product family design methodology is demonstrated. Those components are found in different individually or combined in different studies.

1. **Create the Market Environment:** Any market-oriented study will include some type of a model for the market characteristics.
2. **Identify Players and Firm-specific Dynamics:** Any competitive assessment will include some sort of a competitor study.
3. **Identify Common Platforms:** Even though this step focuses on the technical aspects of product families, the screening, generating candidate designs, and technical evaluation are paramount components of any design effort both for individual products and product families.
4. **Market Simulations:** Particularly in this step, the research effort in this thesis differentiates itself from the status quo. Thanks to the advancements in the micro-economic models, and an identified need for more comprehensive models, IO and MCS was introduced to a product family design problem.
5. **Platform Optimization:** There are many different optimization algorithms for product design and also a specific set of these focus on product families.

### 4.2.2.4 *The Options of Players*

Within the market environment created, there are three types of players. Those are firms with no products in the market, limited amount of products in the market, and a firm that

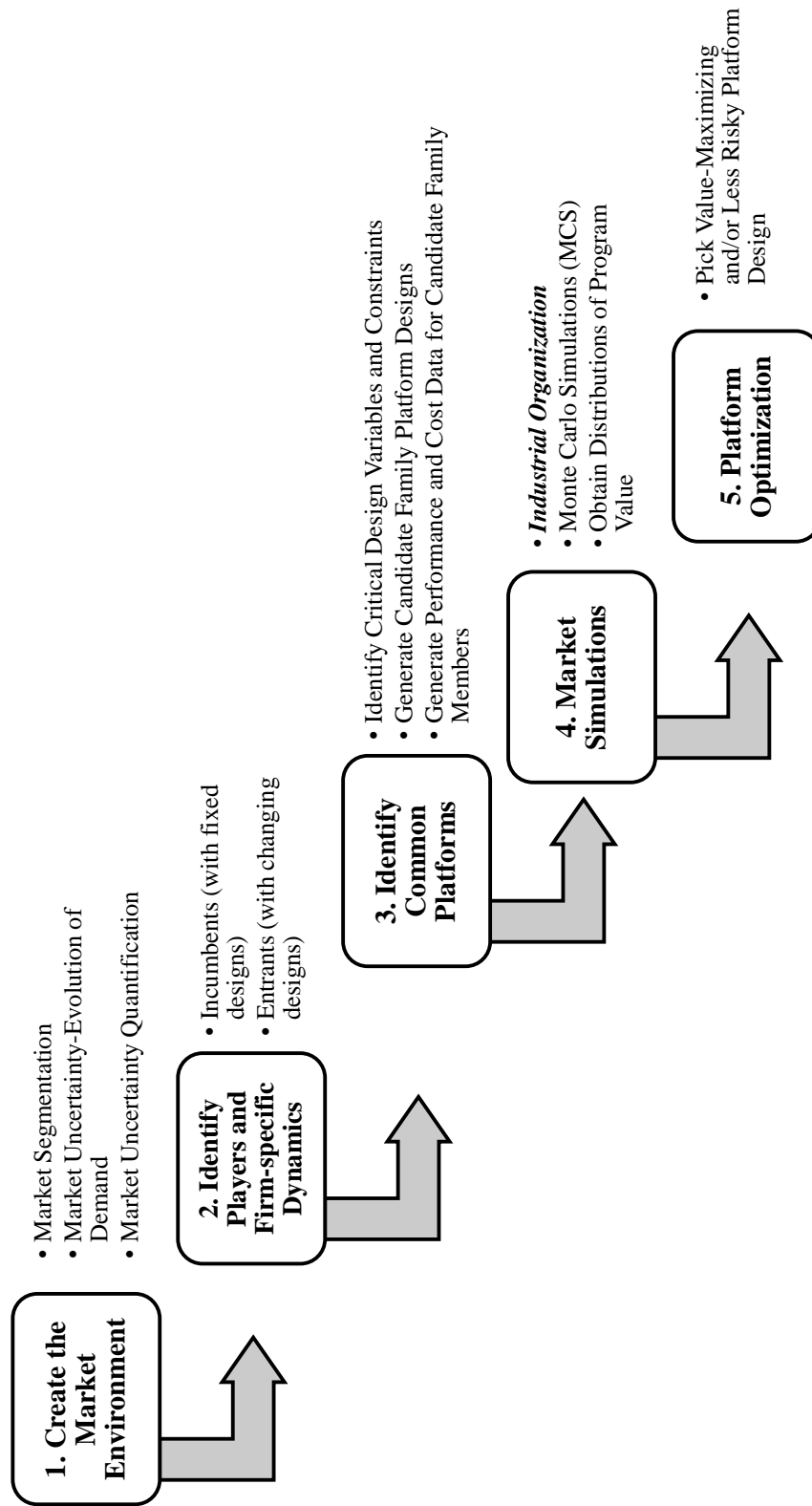


Figure 33: Product Family Design Methodology

offers products across the whole market. They all have different options based on their position.

**Player Type 1:** At each decision epoch, an entrant, a firm with no products in the market, can:

- Observe the market uncertainty, competitors' designs, and competitors' state
- Enter any segment and decide on the production quantity (only one segment can be entered in any year)

$$V^e(s, M) = \max_{X_i^e \in \{0,1,2,3\}} - \sum_{k=1}^3 1 \{X_i^e = k\} x_k^e + \beta \sum_{i', s', M'} V(i^e, s', M') P(i^e, s', M' | i, s, q, M, X, X^e) \quad (13)$$

An important assumption for the entrants in this framework is that they always consider entering at the present time, and do not take the option value of delaying entry into account.

**Player Type 2:** At each decision epoch, an incumbent firm that hasn't maximized its market coverage can:

- Observe the market uncertainty, competitors' designs, and competitors' state
- Enter a segment, that the firm is not present in, and decide on the quantity to be produced for that segment (only one segment can be entered in any year)
- Decide on the production quantity for a segment the firm is already present in.
- Exit a segment, that the company is not making profit

**Player Type 3:** At each decision epoch, an incumbent firm that offers products for all the available segments can:

- Observe the market uncertainty, competitors' designs, and competitors' state.
- Decide on the production quantity for a segment the firm is already present in.
- Exit a segment, that the company is not making profit

$$\begin{aligned}
V(i, s, M) = & \max_{X_i^e, X_j, q_j} \forall j \in J_i - \sum_{k=1}^3 1 \{X_i^e = k\} x_k^e + \sum_{j \in J_i} [X_j \Phi_{jt} + (1 - X_j) \pi_j(i, s, q, M)] \\
& + \beta \sum_{i', s', M'} V(i', s', M') P(i', s', M' | i, s, q, M, X, X^e) \quad (14)
\end{aligned}$$

Equations 13 and 14 are from Benkard's work where he creates an EP model applicable to his research [43][76].  $i$  refers to the firm identity so that  $i$  is finitely bounded above.  $J_i$  is the set of products owned, or offered by firm  $i$ .  $X_i^e$  is the entry decision, whereas the  $X_j$  is the exit decision.  $i', s', M'$  are the state variables one period into the future whereas the  $P$  is the probability distribution generating the transition probabilities.  $q_{jt}$  is the production choice for product  $j$  at time  $t$ .  $\pi_j$  is the per-period profit function as defined in Section 4.1.  $\Phi_{jt}$  is the random scrap value for exiting  $j$  at  $t$ .

Discount factors,  $\beta$ , can be chosen according to different criteria. US government indicates a 7% rate that corresponds to a 14 year time horizon [62]. This simulation will be set for 20 years, indicating a closer number to the industry averages.

The value formulation in this thesis is conceptually similar as entry and exit decisions include different aircraft designs. However in the later steps, approach of Aguirregabiria and Mira is followed to use randomly drawn, privately known shocks[28]. In addition, as a part of the subgame, prices are used instead of quantities.

#### 4.2.2.5 The Platform Design

Each firm enters the dynamic market with a fixed platform design. Wing design is simplified to five design variables such as span, area, taper ratio, thickness-to-chord ratio, and leading edge sweep angle. At the dynamic game level, firms are not allowed to change the platform design. They are only allowed to modify other components to meet the customer requirements if they decide to enter a certain segment.

This second level of the optimization takes the dynamic game simulation as a blackbox for which product platform properties are inputs and the outputs are financial outcomes. In the scenario of a finite number of incumbent firms, and an entrant; the entrant is able to observe the existing designs and create a new design that will yield the most value. Initially, such a study will be performed only for a case of two incumbent firms, and an

entrant. Entrant will be the focal company, for which the framework will be used both for determining the design, economical, and financial decisions.

The following common design variables are directly considered in this research:

- Continuous Variables
  - Wing Area ( $S_w$ ) [ft<sup>2</sup>]
  - Wing Aspect Ratio ( $AR$ ), therefore the wingspan ( $b_w$ ) [ft]
  - Wing Taper Ratio ( $TR, \lambda$ )
  - Wing Leading Edge Sweep ( $\Lambda_{LE}$ ) [deg]
  - Wing thickness-to-chord ratio ( $toc$ )
- Discrete Variables
  - Technology Packages ( $T$ )

#### 4.2.2.6 Simulation Environment

To better describe the simulation environment, following types of cases are defined:

- **Case I - Multiple Incumbent Firms**
  - **Case IA - Multiple Incumbent Firms with Full Product Lines (Fixed Designs):** In this scenario, incumbents have their platform designs fixed and have entered the market in all segments. The framework will only enable determination of optimal policies in a MPE, therefore the program values. Still, MCS can be implemented to see different outcomes. Depending on the simulation parameters, some of the segments may be prematurely exited.
  - **Case IB - Multiple Incumbent Firms with Partial Market Presence (Fixed Designs):** In this scenario, incumbents have their platform designs fixed, but keep the options of entering new segments using the baseline vehicle. The framework will enable to identify optimal entry/exit decisions in this case.
- **Case II - Multiple Incumbent Firms with Entrant(s)**

Table 11: Commonality Observed vs. Assumptions in this Thesis

Subsystem	Commonality Observed	This Thesis
Wing	Common in most families	Common
Empennage	Usually the same in most families	Common
Fuselage	“Stretching” via fuselage plugs	“Stretching” via fuselage plugs
Landing Gear	Common	Common
Nacelle	Common	Common
Engine	Same engine with different thrust ratings	Same engine with different thrust ratings
Engine Accessories	Very similar	Common
Fuel System	Some derivatives may have different fuel tanks	Common
Control Surfaces	Very similar	Common
Hydraulics	Very similar	Common
Avionics	Common	Common
Winglets	Occasionally observed	Not enforced, but a potential case study

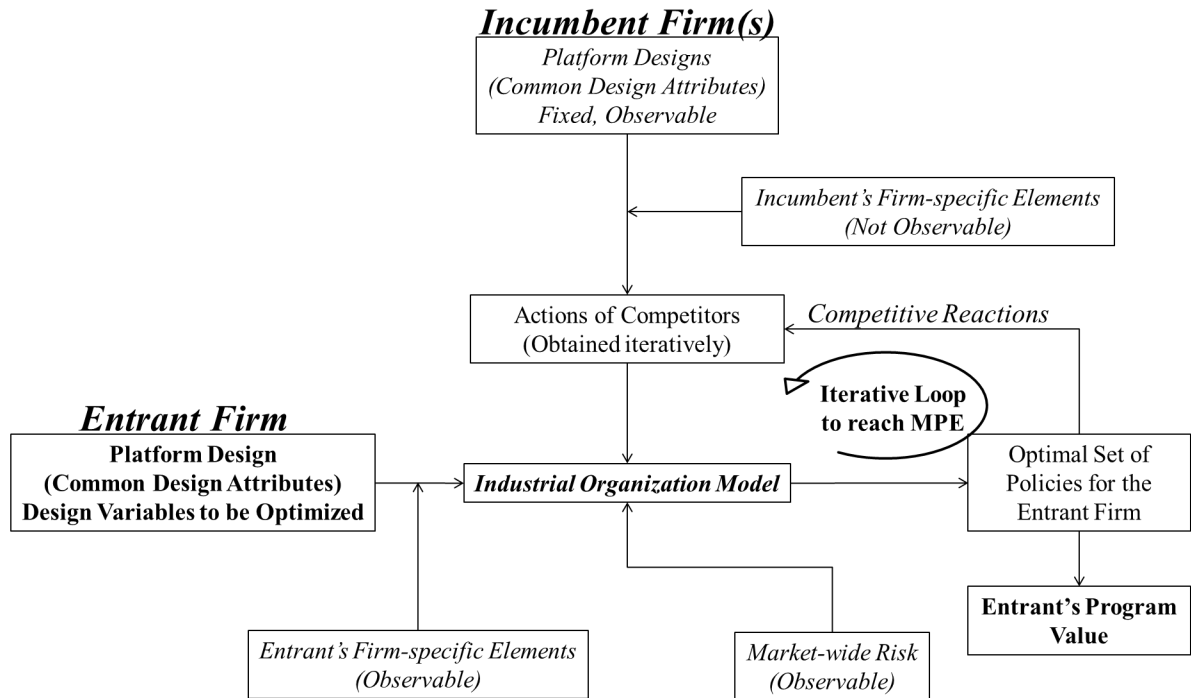


Figure 34: Case IIA featuring One Entrant and at least One Incumbent

- **Case IIA - Multiple Incumbent Firms with a Single Entrant (Entrant Design not Fixed):** In this scenario, the main aim is to identify value-maximizing platform design variables for the entrant. The incumbents are already present in the market, therefore their designs are fixed. This section will build on this example.
- **Case IIB - Multiple Incumbent Firms with Multiple Entrants (Entrant Designs not Fixed):** This is a similar scenario to Case IIA, however it is more complex, as competitive reactions are now not only in means of entry/exit, and strategic control variables, but also designs. A Nash Equilibrium solution is proposed for such cases.

In this thesis, the primary example will be based on **Case IIA** representing the narrow-body market. In this case there is one Player Type 1, and at least one Player Type 2, or Player Type 3. Referring to the methodology flowchart given in Figure 33, this environment describes the stages 4 and 5, Market Simulations and Platform Optimization respectively.

The assumption at this stage is that the necessary information about the industry dynamics, market uncertainty, and firm-specific information is already collected. Also, special to this **Case IIA**, entrant can observe the designs of the incumbents, which is a realistic assumption for a firm considering market entry. In Figure 35, the obtained data is shown in italic, inputs and outputs of consideration are shown in bold, intermediate values are shown in normal fonts. IO model handles a given entrant firm's design, as well as incumbent firm's design in a similar fashion. After several iterations, the equilibrium is reached. Using the optimal policies of the entrant, maximized program value is obtained.

Figure 35 shows an expanded structure of the IO model. First, using a sizing & synthesis tool, performance data for the candidate vehicles are created based on the previously defined mission requirements. Also based on the design and weight data, dynamic cost equations are created. The purpose of this set of equations is to support decision-making of agents within the model. Actions of the competitors are a variable input within this perspective, but this is due to the iterative nature of the process shown in Figure 34. Firm-specific factors have deterministic and stochastic elements as shown in the Internal Firm Dynamics box.

IO model for the **Case IIB**, has only one variable input, the design of Entrant A, as the simulation parameters, as well as incumbent designs are fixed as shown in Figure 36. In Figure 37, the next step of the methodology is presented.

As explained in Section 4.2, the optimization problem could be formulated such as:

$$\min_{S_w, b_w, \Lambda_{LE}, \lambda, toc, T} -E[NPV]$$

$$\text{subject to } b_w < B_w, V_{app,A3} < V_{AAC}, V_{VT,A1} > V_{VT,min}, V_{HT,A1} > V_{HT,min}$$

$$\text{where } E[NPV] = f(S_w, b_w, \Lambda_{LE}, \lambda, toc, T)$$

The Case-IIB is a problem of additional complexity. Two firms that are able to make design changes make problem more complicated than the problem in Case-IIA. For that case, the suggestion is using a Nash Equilibrium concept to find a set of solutions for both firms A and B so that they can't change their designs without losing a portion of the value. The values at the NE are as follows:

$$x_A^* = [S_{w,A}^*, b_{w,A}^*, \Lambda_{LE,A}^*, \lambda_A^*, toc_A^*, T_A]$$



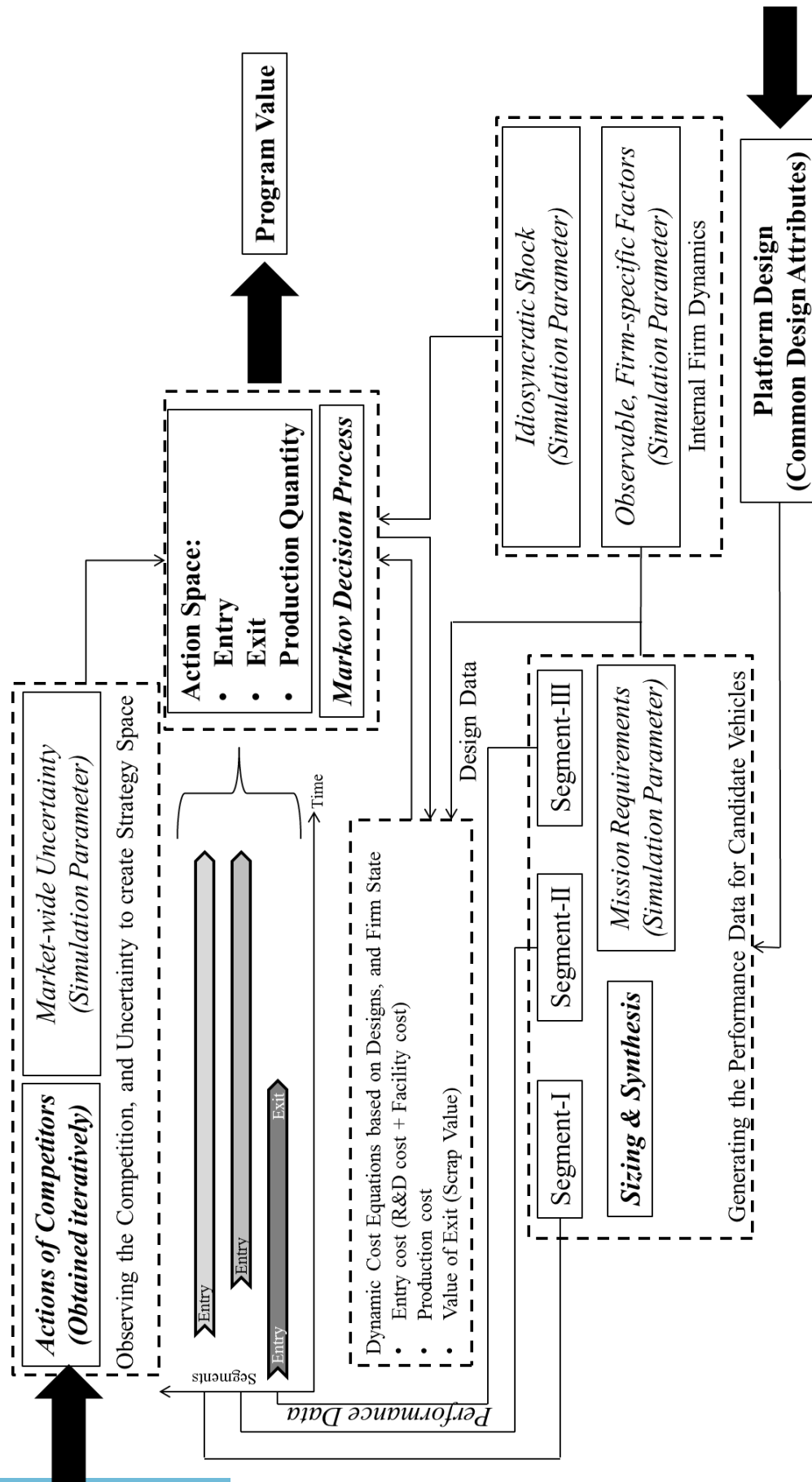


Figure 35: Structure of the Industrial Organization Model

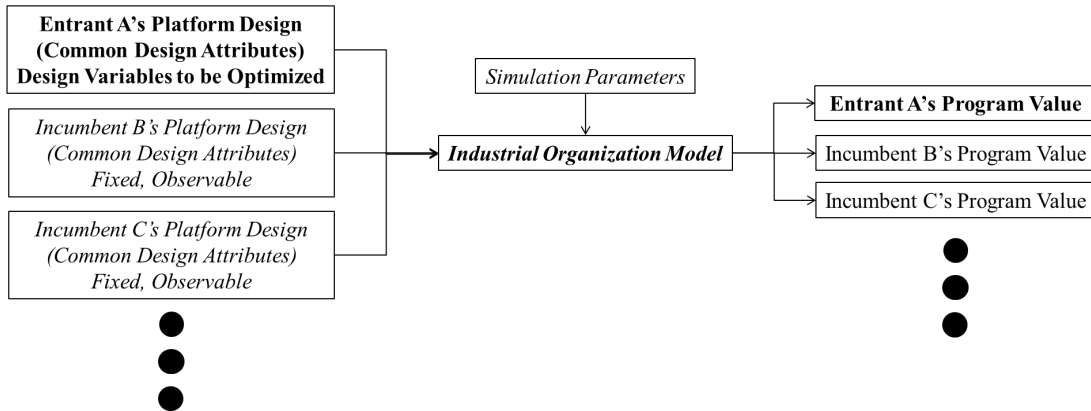


Figure 36: Top-level Inputs and Outputs of the IO Model

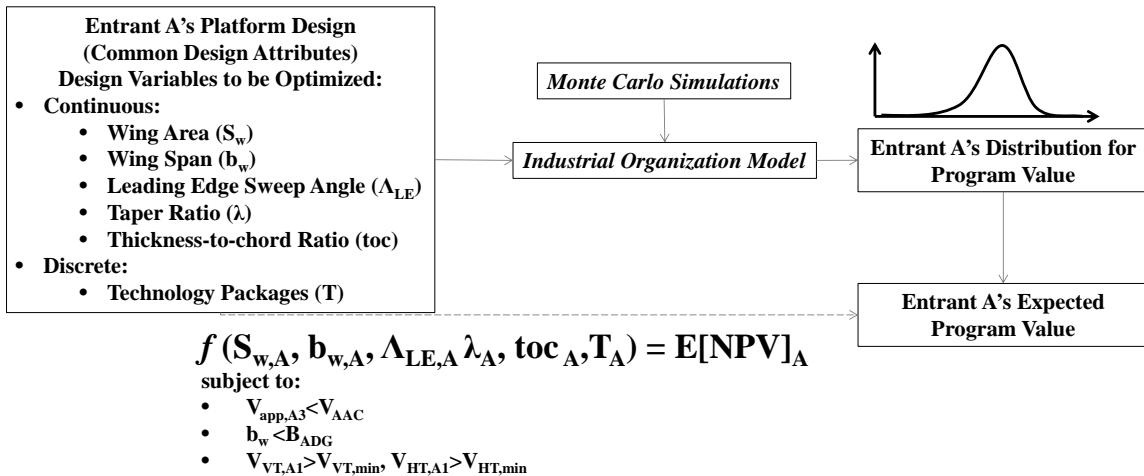


Figure 37: Simplified Form of One Entrant Case (Case-IIA)

$$x_B^* = [S_{w,B}^*, b_{w,B}^*, \Lambda_{LE,B}^*, \lambda_B^*, toc_B^*, T_B]$$

so that at the equilibrium,

$$\frac{\partial E[NPV]_A}{\partial x_A} = 0, \quad \frac{\partial E[NPV]_B}{\partial x_B} = 0$$

These calculations are however, expected to be computationally much more expensive. They also assume that the firms have complete information about each others' design practices which is an unrealistic assumption.

### 4.2.3 Classification of Methodology

The methodology proposed here focuses on the interaction of front-end issues and the core design activities amongst the domains of the product family design literature. This method is a Class II family design optimization, which means that the platform design is variable while the variants are fixed. Variants are fixed because as justified in Chapter 3, different sub-segments are defined according to the seat capacity, and maximum range. Pre-defined seat capacities limit the possible changes that can be implemented on the variants. Commonality is also restricted as the possible common platform is simplified to certain wing specifications. Referring to Figure 4, within the classification of Fujita, this method falls into Group 3, which is a sub-group of Class II [89]. However, this technique differs from existing product family design literature in the sense that the commonality is enabled for the designers to use, but development of derivatives is not forced. In certain case studies, it may be possible to identify scenarios, that an entrant may only serve a certain sub-segment. Therefore, within this framework environment, the resultant program may not be a family program, as it may consist of a single design, or no market entry at all.

Based on Simpson's classification, this formulation addresses a scale-based family design problem, in which the platform is specified a priori, with a single objective, taking into account the manufacturing cost, market demand, and the uncertainty [181]. This is done in two stages as first a platform is defined, and then the family members are introduced if market conditions are favorable. The motivation of the firms is the market pull, as they react to profitable market opportunities. The fundamental assumption to attack these market segments is the implementation of horizontal leveraging strategies, meaning the common

Table 12: Product Family Design Methodology Classification

Commonality	<b>Restricted</b>	Generalized	
Platform Selection	Fixed	<b>Variable</b>	
Variant Design	<b>Fixed</b>	Variable	
Module-based or Scale-based	Module-based	<b>Scale-based</b>	
Platform Specified	<b>A priori</b>	A posteriori	
Single-objective or Multi-objective	<b>Single-objective</b>	Multi-objective	
Supporting Models	<b>Cost model</b>	<b>Market Demand Model</b>	
Number of Stages in Optimization	Single-stage	<b>Two-stage</b>	Multi-stage
Design Motivation	<b>Market Pull</b>	Technology Push	
Leveraging Strategy	Vertical Leveraging	<b>Horizontal Leveraging</b>	Beachhead Approach
Value Metric	<b>Net Present Value</b>	<b>Payback Period</b>	Market Share

Table 13: Competition Properties Down-selection

Number of Competitors	Monopoly	Duopoly	<b>Oligopoly</b>
Strategic Interaction	Decision Theory	<b>Game Theory</b>	
Competitor Reactions	<b>Design Reactions</b>	<b>Price Reactions</b>	
Strategic Decision Variable	<b>Price</b>	Quantity	
Time Dependency	Static	<b>Dynamic</b>	
Game Duration	Finite-horizon	<b>Infinite-horizon</b>	
Decision Epochs	<b>Discrete-time</b>	Continuous-time	
Uncertainty	Deterministic	<b>Stochastic</b>	
Types of Uncertainty	<b>Endogenous</b>	<b>Exogenous</b>	
Number of Products Firms can Offer	Single-product Firms	<b>Multi-product Firms</b>	
Market Entry/Exit	<b>Entry is Permitted</b>	<b>Exit is Permitted</b>	
State Space	Continuous	<b>Discrete</b>	
Action Space	Continuous	<b>Discrete</b>	

platform is used within all segments. Table 13 shows the competition properties down-selection. The choice of using discrete action, and state spaces along with a discrete-time model enables faster calculations.

## CHAPTER V

### PARAMETRIC MODELS

In Chapter 4, the formal decomposition of the proposed methodology to test the hypothesis is shown. In order to fully realize the methodology presented in Figure 33, certain parametric models are needed. Creation of these models will enable us to complete the first and third step of the presented methodology. Specifically, this chapter deals with the underlined elements:

1. Create the Market Environment

(a) Market Segmentation

(b) Market Uncertainty-Evolution of Demand

(c) Demand Model

2. Identify Players and Firm-specific Dynamics

(a) Incumbents (with observable designs)

(b) Entrants (with changing designs)

3. Identify Common Platforms

(a) Identify Critical Design Variables

i. Identify Constraints on Design Variables

(b) Generate Candidate Family Platform Designs

(c) Generate Performance and Cost Data for Candidate Family Members

i. Identify Performance/Cost Constraints

ii. Screen for Performance/Cost Constraints

4. Market Simulations

- (a) Industrial Organization
- (b) Monte Carlo Simulations
- (c) Obtain Distributions of Program Value

## 5. Platform Optimization

- (a) Pick value-maximizing platform design
  - i. One-step solution for one entrant
  - ii. Sequential Nash Equilibrium Solution for two or more entrants

### ***5.1 Market Environment***

#### **5.1.1 Segmentation of Market Space**

In this framework, the market space  $\mathbf{C}$  is represented as a 2-dimensional space with product specifications normalized to  $[0,1]$ . In this particular case, observing the historical trends in the narrow-body market, focus is on the range and the passenger capacity for a fully-loaded typical 2-class configuration.

As the next step, the seat-range combinations are normalized so that the values fall within the range  $[0,1]$ . This step is important for having a better explanatory model. As explained in the next section, when comparing products for quantifying certain factors such as the demand shift and cannibalization, the Euclidian distance between the design points on  $\mathbf{R}^2$  is used. This allows the model to ignore the absolute value changes and focus on the relative changes with respect to other designs in the same segment. For instance, the impact of a 10-seat increase in the passenger capacity of a plane has a bigger impact on the favorability of the model than a 10NM range increase. The market boundaries are selected to be between 100 to 220 for 2-class typical seating capacity and 2500NM to 4500NM for the corresponding range at the maximum 2-class seating. The ranges of the design space thus define the weighting of the importance of variation from the customer points.

To ease the simulations and focus on the design side of the problem where more platform designs can be tested for their performance, a few number of discrete mission requirements for design points are fixed. Shown in Table 14, new sub-segments of the narrow-body market

Table 14: Assumed Market Segments for the Case Study

Segment	Seats	Range (NM)	Fuselage Length (ft)
Narrow-Body I (NB-I)	132	3750	110.4
Narrow-Body II (NB-II)	162	3250	129.6
Narrow-Body III (NB-III)	192	2750	148.8

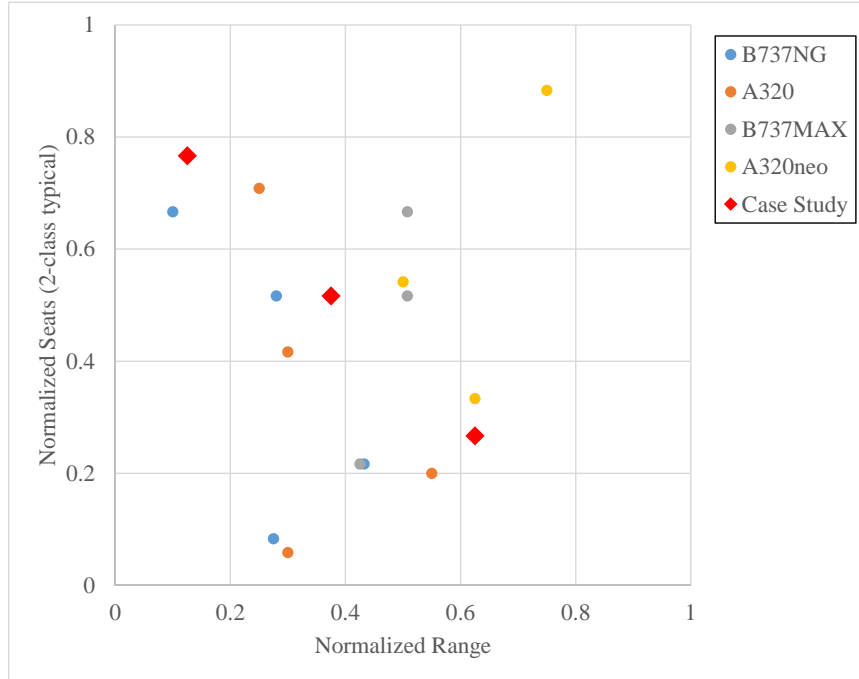


Figure 38: Distribution of Current Aircraft and the Case Study on Market Space C

are defined. Even though the framework enables more exhaustive studies where a high number of design points can be analyzed, due to the “curse of dimensionality”, estimation of the equilibrium is computationally expensive for those types of comprehensive studies.

Combining this assumption with the Equation 3, the fuselage lengths of the case study aircraft are directly fixed. It is also directly intuitive to assume the fuselage length is primarily a function of the number of seats, and the comfort level, therefore the technology will have little impact on the fuselage dimensions as the concepts explored within this thesis are all tube&wing configurations.

### 5.1.2 The Case for the Evolution of Demand

Market data for the narrow-body aircraft spanning 14 years between 1999-2012 is compiled from various sources [158, 85][24]. Both delivery and order per year per plane type data and the corresponding list price were obtained. Number of orders were picked as a market performance measure. It is possible to object such an approach as some orders are tentative and can eventually be cancelled. Also, there is usually a lag between the order and the delivery of the plane. However, number of orders better represent the volatility of the market and how different customers react to different designs when factors such as the global economy, demand for air transportation, and fuel prices fluctuate. On the other hand, delivery values don't vary greatly throughout the years despite market-wide shocks. This is primarily due to the backlog and cost of change in production capacity. Aircraft manufacturers, as strategic players, plan ahead and keep a steady production output.

The data set also includes the list prices of each 8 narrow-body aircraft for the 14 years in consideration. Obtaining the actual transaction prices is very difficult as these kind of special deals including green stamps and other discounts are usually made privately. As a rule of thumb though, Airbus is known to make 43% discount over the list price on average whereas this percentage is about 45% for Boeing [9]. Discounts and other price variability are also impacted by the delivery dates as well as the specific cabin configurations. In the model, the variability in airline specific seating demands are ignored and the focus is solely on the desired derivative.

Also, "outside goods" are indirectly incorporated in this model. Outside goods are passively involved as they don't react e.g. price adjustments but imply that if the prices in the narrow-body market are too high, the demand may shift to outside the market such as RJ and even wide-body markets. Outside goods also consist of used-goods market as second-hand market forms a significant portion of the transactions in the aircraft industry today. This framework however, can be extended to use quantitative data to model inter-market dependencies and interactions.

At a given year, the number of orders per vehicle is used as well as normalized product characteristics. The customers are assumed to be distributed continuously over the market



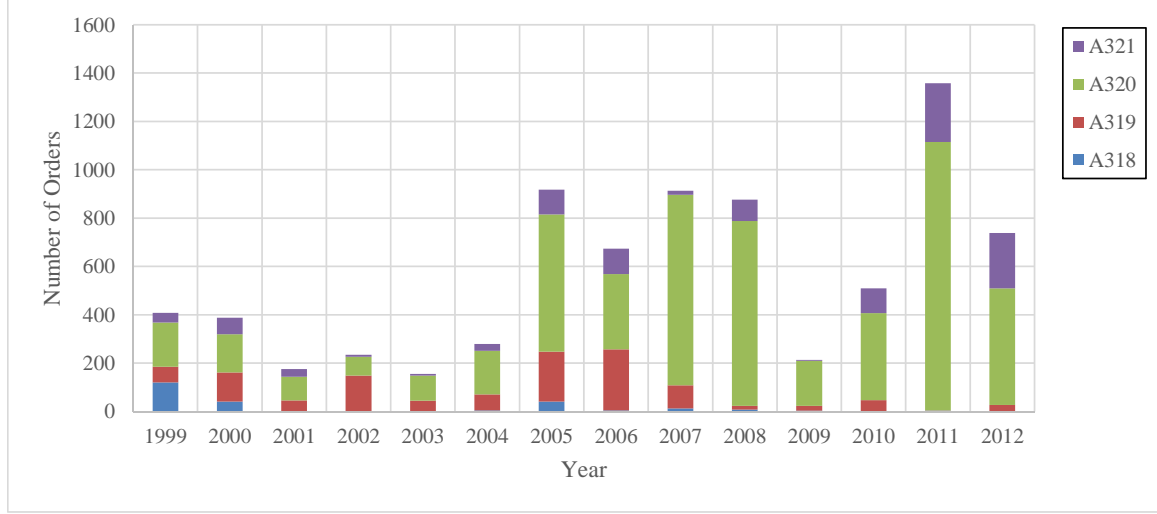


Figure 39: A320 Family Number of Orders 1999-2012

space. At each location  $z \in C$ , there are  $\Phi_t(z)$  number of customers, which each one of them corresponds to one acquisition. The distribution of the customers is assumed to be a bivariate normal distribution which can be defined by the mean on  $x$  and  $y$  ( $\mu_x, \mu_y$ ), variances on  $x$  and  $y$  separately ( $var(X), var(Y)$ ), covariance on  $x$  and  $y$  ( $cov(X, Y)$ ), and the size of the population  $M_t$  which is the integral of the population distributed around the market space shown in Equation 15. In this example,  $x$  represents the normalized range at design point and  $y$  represents the normalized 2-class seat capacity.

$$M_t = \int_C \Phi_t(dz) \quad (15)$$

Since 1980, the demand for air travel, a major factor in the number of new planes needed, has been steadily increasing despite 4 recessions, 2 financial crises, 2 Gulf wars, an oil shock, a near pandemic and 9/11 [158]. Forecasting future demand for a complex industry under both macroeconomic and microeconomic factors is an entirely separate field. Boeing estimates 26,730 new deliveries in the next 20 years where as the Airbus estimate is at 22,900 (~1340 and 1145 per year on average respectively) [158, 85]. It is possible to assume the continuation of Business-As-Usual (BAU) scenarios where the market doesn't receive shocks as the shocks such as the ones listed previously are quite unpredictable. However, some perturbation from the usual case is applied and there are "low", "regular",

Table 15: Bivariate Normal Distribution Fit Evolution over Different Periods

Period	Mean Range	Mean Seats	SD Range	SD Seats	Covariance	Average Yearly Demand
1999-2000	0.3801	0.3638	0.1434	0.1639	-0.0225	634
2001-2002	0.2897	0.5012	0.1183	0.1655	-0.0170	368
2003-2004	0.3611	0.3874	0.1246	0.1523	-0.0179	384.5
2005-2006	0.3280	0.4186	0.1118	0.1506	-0.0154	1411
2007-2008	0.3117	0.4542	0.0899	0.1208	-0.0096	1722.5
2009-2010	0.2857	0.4691	0.0695	0.1026	-0.0062	692
2011-2012	0.2719	0.5142	0.0990	0.1235	-0.0107	1545
<b>1999-2012</b>	<b>0.3114</b>	<b>0.4523</b>	<b>0.1099</b>	<b>0.1435</b>	<b>-0.01439</b>	<b>965.2</b>

and “high” demand scenarios.

Apart from the overall market demand, the distribution of the consumer demand is also important. It is possible to argue that over the decades, bigger narrow-body aircraft such as the mid-size Boeing 757 has become less popular and LCA market has polarized between more differentiated narrow and wide-body segments. As an additional example, the Asian narrow-body market, a fast-growing market, prefers larger narrow-body aircraft [158]. Such factors indicate that the future preferences of airlines will be quite different than their past or present choices and the new market segmentations may be necessary. This is also observable in Figure 38 where the new generations of the families can carry more passengers over longer distances which is, in part, enabled by more efficient designs which will be explored in the narrow-body case study.

Table 15 is not a result of actual operations but a weighted collection of the maximum capabilities of sold narrow-body aircraft. It should also be noted that due to wing loading limitations, family members using the same wing usually have less range at higher seat capacities. Therefore, since the design points of the aircraft in consideration tend to move diagonally on the Payload-Range diagram, it is possible to assume that in the future even the A319neo and B737 MAX7 class may slowly disappear similar to the class of A318 and B737-600. The overall direction of the market is observed to favor bigger airplanes as the smaller segments perhaps face a demand shift to RJs or to bigger derivatives because of increasing fuel costs.

Therefore a market structure assumed has a demand distribution that is mainly focused

at NB-II segment. On a typical scenario when all firms are present in the market with full product lines, the NB-II segment represents about two thirds of the total demand. NB-I and NB-III segments represent about 10% and 25% respectively.

## **5.2 Performance Model**

### **5.2.1 Screening of Critical Design Variables**

In order to create a fully parametric design-for-market environment, there is need for a notional narrow-body aircraft. To perform this step, NASA's Flight Optimization Software (FLOPS) is chosen. FLOPS is a multidisciplinary set of modules for the conceptual design of aircraft that can estimate the weight, aerodynamics, propulsion data, mission performance, and cost. Some of the modules rely on empirical data whereas some calculations are physics-based [126].

Previously the following continuous platform design variables were identified to be critical in designing an aircraft common platform:

- Wing Area ( $S_w$ ) [ft<sup>2</sup>]
- Wing Aspect Ratio ( $AR$ ), therefore the wingspan ( $b_w$ ) [ft]
- Wing Taper Ratio ( $TR, \lambda$ )
- Wing Leading Edge Sweep [deg] ( $\Lambda_{LE}$ )
- Wing thickness-to-chord ratio ( $toc$ )

Since this methodology has the potential to be computationally expensive, it is important to perform an initial screening to see if any of these design variables are more or less important than the others. For this step, a representative B737-800 model was used in FLOPS environment with all the geometry except the design variables in question fixed. For a simple analysis, their effects on the fuel weight for the 2-class typical seating and maximum range mission are obtained. A latin-hypercube Design of Experiments (DOE) of 1000 runs are run which is accompanied by a response surface fitting to reach a  $R^2$  of 0.999. Within the specified input ranges, aspect ratio is observed to have the highest impact on the

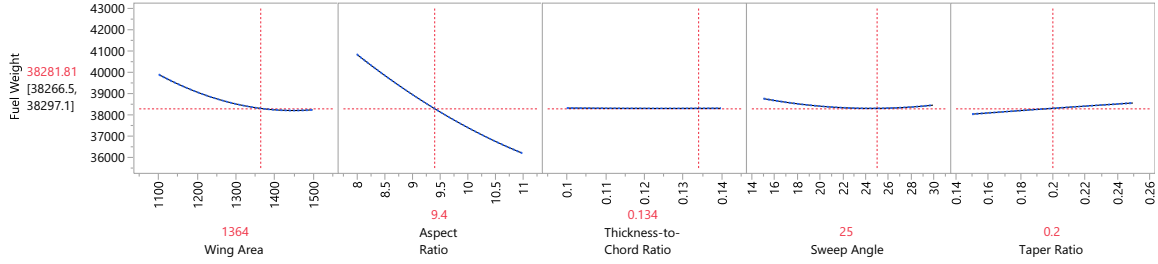


Figure 40: Sensitivity of Fuel Weight to Wing Geometry for B737-800

fuel weight whereas the wing area is observed to have impact only after dramatic changes. Thickness-to-chord ratio, sweep angle, and taper ratio are found to have insignificant effect. Even though the aspect ratio is very important, due to regulatory constraints as well as material and structural flutter limitations, it will be limited leaving wing area as the only possible design input with some impact. Results are summarized in Figure 40.

#### 5.2.1.1 Addition of Technologies

As Figure 40 suggests, within the narrowed down design space of the narrow-body case study, the sensitivity of the continuous design variables are limited except the wing area which is bounded by the structural and regulatory limits. Therefore, the technology k-factors are introduced as in Technology Impact Forecasting method (TIF) [118]. At this step, the following observation is also introduced:

**Observation 10:** *Across generations, new families are not necessarily new designs but improvements with addition of new technologies. At the conceptual design level, design changes are minimal.*

Performance Improvement Packages (PIP) are a common way to improve an already existing family with reduced development costs. In the case study, the design problem will be further simplified into a technology selection problem. Keeping the initially specified design variables constant, now this problem becomes a discrete selection of value-adding technologies from a given technology portfolio. Originally the mathematical demonstration of mapping of the design variables to a single value of an expected NPV was shown as:

$$E[NPV] = f(S_w, b_w, \Lambda_{LE}, \lambda, toc, T)$$

Following the screening process demonstrated in Figure 40, this formulation becomes

Table 16: A320neo Family Main Characteristics [7]

Specification	A319neo	A320neo	A321neo
Typical Seating	140	165	206
Max Seating	160	189	240
Range (NM)	3750	3500	4000
Max TOGW (lbs)	166400	174200	213800
Max Zero Fuel Weight (lbs)	132900	141800	166700
Max Fuel Capacity (USg)	7060	7060	8700
Overall Length (ft)	111	123.2	146
Cabin Width (ft)	12.1	12.1	12.1
Wing Span (ft)	117.4	117.4	117.4
Horizontal Tail Area (ft <sup>2</sup> )	333.7	333.7	333.7
Vertical Tail Area (ft <sup>2</sup> )	231.4	231.4	231.4

only a function of the chosen technology scenarios.

$$E[NPV] = f(T)$$

Technological uncertainty and quantifying its impact in a probabilistic manner have been thoroughly investigated in the past [118]. However, within this thesis, the economical impact of these technologies are investigated in an uncertain market environment. In order to isolate the uncertainty that is associated with the development cost, duration and the actual impact of a given technology, deterministic values are assumed for these amounts.

### 5.2.2 Parametric Design Environment

FLOPS environment is used to design the new hypothetical narrow-body family competitor. The main issue with using FLOPS for a family design instead of an independent design is that FLOPS does not have embedded capability for commonality applications. Therefore A320neo family is picked to test the capability of FLOPS to estimate the published data via keeping fore-mentioned common specifications and varying derivative-specific variables. A summary of the fundamental specifications for the A320neo family is provided in Table 16. FLOPS needs to be calibrated to match the published TOGW and the fuel weight of A320neo. To represent the performance improvements of the new family with “sharklets”, more efficient engines, and weight savings, new adjustments were done for the calibration factors in FLOPS.

The aim in this part of the effort was to gauge the reliability of a parametric conceptual

Table 17: Comparison of the FLOPS Model with Posted Weights

Response	Source	A319neo	A320neo	A321neo
Fuel Weight (lbs)	Posted	48008	48008	59160
	Model	47679	47240	59618
TOGW (lbs)	Posted	166000	174000	206000
	Model	163053	177976	221725
Empty Weight (lbs)	Estimated OEW	89900	93900	106900
	Model	77739	86620	106132

design environment in which the “rubber engine” can be sized to meet the thrust-to-weight requirements, fuselage can be stretched or shrunk to meet cabin area requirements. Airbus defines the Operational Empty Weight (OEW) as the “Weight of structure, powerplant, furnishings, systems, and other items of equipment that are an integral part of a particular aircraft configuration plus the operator’s items. The operator’s items are the flight and cabin crew and their baggage, unusable fuel, engine oil, emergency equipment, toilet chemical and fluids, galley structure, catering equipment, passenger seats and life vests, documents, etc.” [7]. The standard Empty Weight from FLOPS is used although it is recognized that the OEW would be higher due to the additional components listed.

#### 5.2.2.1 Empennage Considerations

FLOPS uses a slightly different way to estimate the authority of vertical and horizontal tail on the aircraft stability and control than the ones shown in Equation 16 and 17. Instead of using more complicated but more reliable forms of estimating the moment coefficients by using chord lengths, such as the ones shown in Equation 1 and 2, FLOPS uses the fuselage length ( $l_f$ ) as a proportional variable to the moment arm.

$$S_{VT} = \frac{c_{VT}S_W}{l_f} \times \sqrt{S_w/AR} \quad (16)$$

$$S_{HT} = \frac{c_{HT}S_W}{l_f} \times \sqrt{S_w/AR} \quad (17)$$

Using the geometric data of B737MAX and A320neo, the coefficients are estimated for all family members and shown on Table 18. Figure 41 also shows the impact of the tail size on empty weight and TOGW implying both the weight and drag penalties for this

Table 18: Volumetric Tail Coefficients for B737MAX and A320neo

Aircraft Type	Vertical Tail Coefficient	Horizontal Tail Coefficient
B737 MAX7	2.05	2.54
B737 MAX8	2.40	2.98
B737 MAX9	2.56	3.18
A319neo	1.72	2.49
A320neo	1.92	2.77
A321neo	2.27	3.28

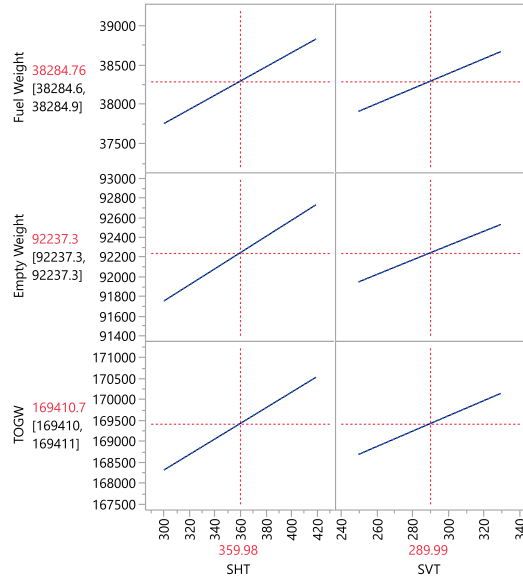


Figure 41: Impact of Tail Size on the Aircraft Weight (B737-800 representation)

representation of B737-800. This study is just intended to emphasize the importance of minimizing the tail size as long as an acceptable coefficient is obtained. Based on the Boeing and Airbus designs, 2.0 for the vertical tail coefficient and 2.5 for the horizontal tail coefficient are assumed to be reasonable values for the notional design space.

Based on the volumetric tail coefficients of the existing designs, it is possible to argue that the tail is sized for the smallest derivative. Perhaps a smaller tail would be sufficient for the bigger derivatives, if a company only focused in entering the bigger side of the narrow-body market, without extending the product line to the smaller narrow-body aircraft. It is also possible to have a family of aircraft sharing the same wing but different empennage such as the A320 family. However, it is assumed to be economically unreasonable to do so and proceeding with the single empennage design is expected to be a viable option.

Table 19: Aircraft Approach Category [34]

Aircraft Approach Category	Indicated Airspeed
A	Less than 169 km/h (91 kts)
B	169 km/h (91 kt) or more but less than 224 km/h (121 kts)
C	224 km/h (121 kt) or more but less than 261 km/h (141 kts)
D	261 km/h (141 kt) or more but less than 307 km/h (166 kts)

### 5.2.2.2 Aircraft Approach Category

Aircraft approach category is grouping of aircraft based on the indicated airspeed at threshold[21].

Although not as critical as the wingspan or tail size constraints, it is important to keep the approach velocity at reasonable values that are within the same range as the comparable aircraft of today. As the biggest derivatives, both A321 and B737-900 fall within the category D due to their heavier landing weight. Approach velocity directly influences the landing field length impacting the utilization of the aircraft at shorter fields. Therefore in the narrow-body case study, the approach speed is implemented as a constraining element. Even though not always true, considering the correlation between the maximum takeoff gross weight and maximum landing weight, the wing loading in this study is limited to that of B737 MAX9's. The value obtained from the published data is 144lb/ft<sup>2</sup>[10]. This is implemented as a constraint on the size of the wing.

$$V_{app} = 1.3 * V_{S0} \quad (18)$$

$$V_{S0} = \sqrt{\frac{2}{\rho C_{L(Landing)}} \frac{MLW}{S_w}} \quad (19)$$

where

$V_{app}$  is the approach velocity

$V_{S0}$  is the stall speed at landing configuration

$\rho$  is the air density

$C_{L(Landing)}$  is the lift coefficient at landing configuration



$MLW$  is the maximum landing weight

$S_w$  is the reference wing area

### 5.2.2.3 Operational Considerations

Even though the aircraft sizing and synthesis is usually influenced by the extreme capabilities of the vehicle which form the edges of the flight envelope, airlines usually don't operate close to those edges. Therefore, it is possible to argue, from the airlines perspective, that the vehicle's fuel performance is more crucial at those "mid-points" than the extremities. To better enhance the model, although the sizing is matched to the design points which indicate the limits of possible flights, it is reasonable to assume that the airlines are more interested in the fuel consumption of the aircraft at those commonly used operating regimes. Due to limited data, such an assessment can only be limited to analyzing the domestic operations in US. Using FAA's T-100 data from 2015, some of the popular routes flown by B737NGs and A320s are identified. This database, also known as the Air Carrier Statistics Database is a compilation of the monthly reports of the certificated US air carriers. It is a publicly available set of data that is used by aviation industry to analyze the patterns and the evolution in airlines operations.

As presented in Table 20, the bigger variants fly longer distances more often. However, despite different utilization rates, the majority of the flights are performed by the smaller models resulting in higher sales. In 2015, the average distance flown by the two families in consideration was about 1060NM. However, North American sales only form about 16% of the new generation narrow-body sales [4]. In other prominent markets such as Southeast Asia and Europe, it is possible to assume the average stage-lengths will be shorter although some of those will probably be performed by RJs.

## 5.3 Cost Model

To complete the simulation primitives, the following needs to be quantified:

- R&D Investment

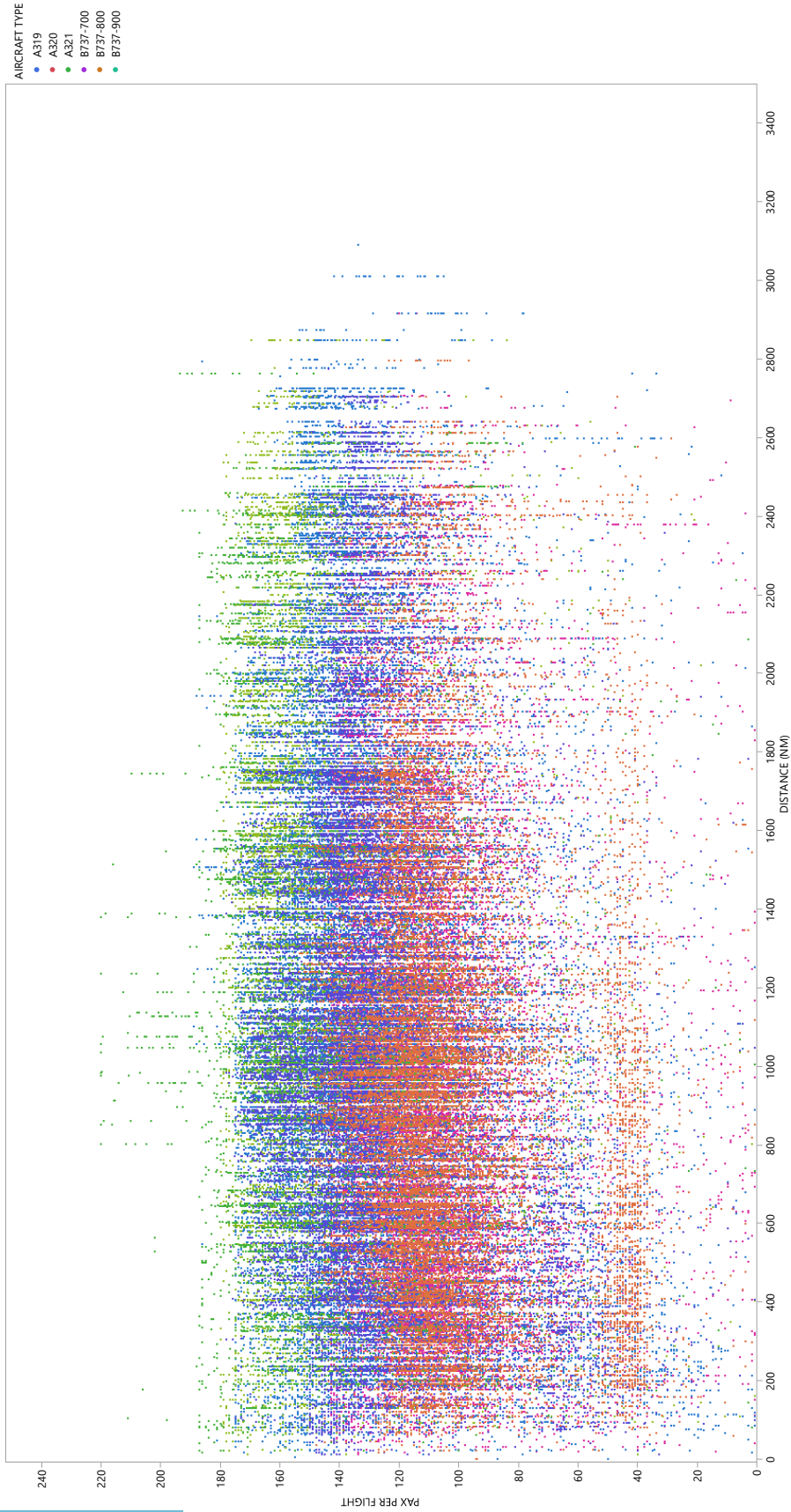


Figure 42: US Domestic Flights in 2015 by B737NG and A320 Families

Table 20: Summary of US Domestic Operations in 2015

Aircraft Type	Mean Stage-Length (NM)	Departures Performed
B737-700	793.74	893109
B737-800	1258.89	782796
B737-900ER	1350.10	225983
A319	878.17	457532
A320	1135.94	647238
A321	1303.40	206374
<b>Overall</b>	<b>1059.89</b>	<b>3213032</b>

- Baseline Aircraft R&D cost: The base cost to enter the market
- Derivative Aircraft Additional R&D cost: The optional cost to expand the product line

- Production-Related Costs

- Marginal Cost: The average cost of producing a certain aircraft that the firm already can produce
- Fixed Cost: The production cost even when there is no production in place

### 5.3.1 R&D Investment

In this game, it will be assumed that all the firms within the market simulation have already invested a substantial amount in R&D costs. This will be reflected by the initial investment put into developing the smallest derivative NB-I. This assumption does not only make sense from a historical perspective such as Boeing starting to develop the B737s by the smallest B737-100, but also enables a simpler dynamic programming problem. The calibrated FLOPS/ALCCA environment is used to estimate the development cost in 2015 US dollars. ALCCA is the Aircraft Life Cycle Cost Analysis program developed by NASA and improved by ASDL. One disadvantage of ALCCA's estimation is that it is a strong function of weight. Although this is mainly true, it fails to account for cases such as an expensive weight reduction technology that would lower the weight of the vehicle in the expense of increased R&D costs. Using this method, the required investment for a narrow-body is estimated to be around 9-12 billion USD.

For estimating the cost of development for a derivative aircraft, an approach similar to that of Fujita is used which is presented in Section 4.1.3 [88]. Instead of using the vehicle component weights independently, the estimated weight-based R&D costs, which are obtained as if those designs were developed independently, are obtained from FLOPS as a measure of similarity. It is possible to argue that there may be more complications to the derivative development cost than just the independent development margins, therefore a fixed element and a coefficient are introduced to the derivative R&D estimation.

$$D_{NB-II}^d = \alpha^d + \beta^d(D_{NB-II}^i - D_{NB-I}^i) \quad (20)$$

$$D_{NB-III}^d = \alpha^d + \beta^d(D_{NB-III}^i - D_{NB-I}^i) \quad (21)$$

where

$D_{NB-II}^d$  is the development cost of NB-II from NB-I

$D_{NB-II}^i$  is the independent development cost of NB-II (without a prior know-how)

$\alpha^d$  is the fixed development cost of a new derivative

$\beta^d$  is the coefficient for the variable derivative development cost

It is important to note that these development costs are introduced to demonstrate the parametric baseline model. For this instance, specifically for the A320neo, Airbus was able to use the A320 design extensively. This scenario assumes “from scratch” development of a new family of aircraft. The hypothetical market entrant firm in the case study will develop such aircraft with no prior know-how. However, in the dynamic simulation environment in which the discounted cash flow is the main focus, the timing of such investment may have an impact on the net present value of the program particularly due to discount factors. In addition to these scenarios, another value,  $MEC_i$ , is introduced as the main entry cost for the game. Any player present in the game is assumed to have already invested a substantial amount in R&D. This amount is assumed to be USD 5 billion less than the independent development cost of the smallest derivative NB-I. This assumption is debatable, however it

enables reduce a potentially two-stage dynamic entry game into a single stage. The firm can then invest another  $D^d_{NB-I}$  to develop the first derivative if wanted.

### 5.3.2 Production-Related Costs

Reductions in production-related cost savings are an important advantage of product families over independent designs. In Section 4.1.3, a method that can combine the learning curve effects with commonality effects was shown. In the work of Benkard, it is shown that the learning curve effects can explain some of the pricing behavior in aircraft market and can be analyzed by IO models [43, 42]. In this case study, three assumptions are made:

1. Commonality between narrow-body aircraft are so significant that they can be assumed to benefit from the learning curve effects as if they were a single type of aircraft.
2. Over the program lifecycle, sale numbers in narrow-body market are so high that the marginal costs can be assumed to reach the Long-run Marginal Cost (LRMC) (Table 21)
3. Excluding the discount rates from the aircraft list prices, aircraft manufacturers tend to price aircraft quite steadily. Based on the figures, although these are list prices, it is possible to argue that the pricing is not done over the dynamic marginal cost but from a more linearized value. Although steady increase in price compared to dynamic cost fluctuations that occur primarily in the first few years after introduction means big mark-up changes, it is assumed that this doesn't influence the decisions of forward-looking strategic players.

Neglecting the impact of dynamic experience level as a part of the state vector of a firm helps us reduce the effects of "curse of dimensionality". The benefits of this assumption is shown in Section 6.1.2.1.

There is a total of 6967 for B737NG sales and 7931 for A320ceo sales [24]. Even though new players such as Bombardier is entering the market to reduce the duopoly's market

Table 21: Estimated Marginal Costs at Different Production Volumes for Parametric A320neo Model (in million US Dollars)

Derivative	500units	1000units	2000units	4000 units
A319neo	61.61	58.96	54.45	48.65
A320neo	65.415	62.68	58.03	51.92
A321neo	74.285	71.39	66.41	59.82

share, narrow-body market is growing steadily and roughly speaking, can sustain such high production volumes per firm.

Since manufacturing cost data is an important, private, and strategic information, manufacturers are reluctant to provide clues. In order to validate these marginal cost values, assumption of 45% discount rate over the list price of A320neo aircraft in 2015 is used.

These markup values are within the values in literature [103]. Roughly speaking, 6-7 million USD of profit per plane at 10 billion USD development cost would bring the breakeven number of planes to about 1500 which would indicate that both B737NG and A320 families are extremely profitable.

In the dynamic model, prices of vehicles are endogenous control variable that can be changed every year. Therefore, these static considerations should be only interpreted as a validation to the weight-based parametric cost calculation. In the IO model, these MC values will be used as inputs to the simulation although the total number of units sold can change and is one of the outputs of the IO model. It is possible that not all the designs are successful enough to accumulate about 4000 unit sales to reach a LRMC and implementing a feedback mechanism for the production volume would increase the computational burden. Therefore, as long as the assumed production volume and the total sales values are “close enough”, these assumptions will be considered to be valid. The fixed (e.g. facility) cost component is neglected and instead, the assumption is that those are already distributed amongst the marginal cost. These production volume expectations are justified by the number of orders and deliveries in the market.

Table 22: Estimated Markup Values at Different Production Volumes (Prices in million US Dollars)

Derivative	List Price	Estimated Transaction Price	Markup at 2000	Markup at 4000
A319neo	97.5	53.625	-1.6%	10.2%
A320neo	106.2	58.41	0.6%	12.5%
A321neo	124.4	68.42	3.0%	14.3%

## 5.4 Demand Model

### 5.4.1 Value Considerations

In Section 2.7, it was shown how concept of value could vary between different entities. The following perspectives were specifically considered:

- **Manufacturer perspective:** The value of the overall aircraft family program (Shareholder value)
- **Airline perspective:** The value of a certain vehicle based on the airline operations (Customer value)

In reality, these definitions are closely interconnected. In Figure 43, a simple schematic is used to portray their connectivity. If the firms can offer “value”, then this value propagates through different stakeholders. Considering the Air Transportation System, such a chain can be extended to airport managers, passengers, governments etc..

It is important to note that, within the scope of this thesis, the revenue side of the airline operations isn’t analyzed or modeled. From an aircraft designer point of view, we assume that the operations will be similar as long as the following design characteristics are kept constant:

- **Seats:** In each individual segment, even an extra row can significantly change the ticket pricing, and capacity allocation processes for airlines
- **Cruise Mach Number:** Faster travel can cause increased fuel burn but increase ASM per vehicle for a given time period potentially increasing both revenue and cost. Such an interaction is complicated and kept out of scope of this thesis.

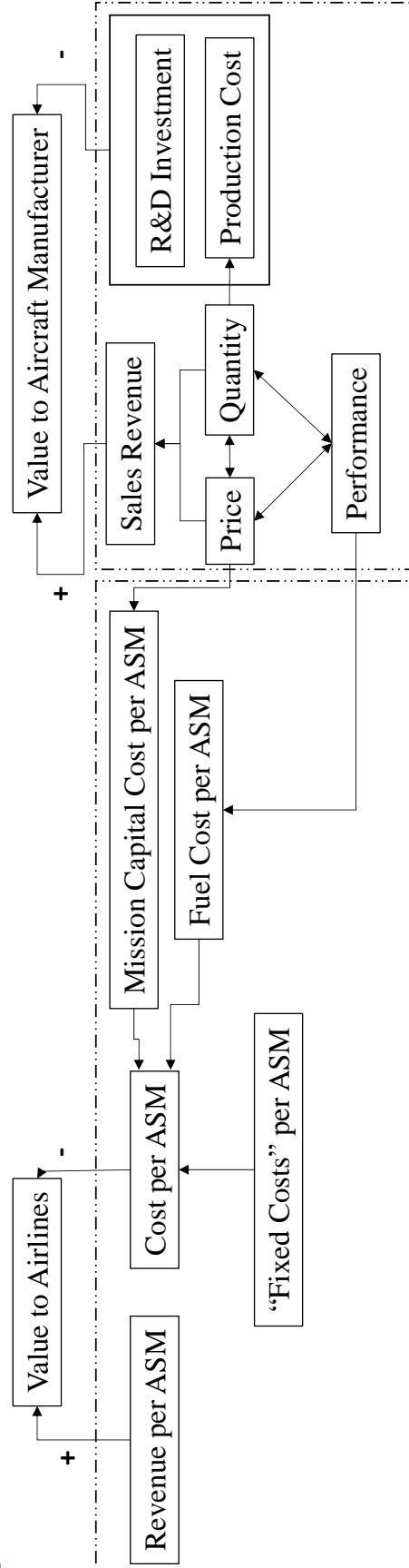


Figure 43: Value Transfer between Stakeholders



- Aircraft Design Group: Same ADG ensures the new replacement aircraft can utilize the ground infrastructure in a similar fashion

#### 5.4.2 Value Transfer

In a competitive environment such as the narrow-body market, manufacturers need to offer cheaper and more fuel efficient airplanes with an extensive product line. These three important forces are essential in this experimental setup.

- Some Definitions within Direct Airline Operating Costs
  - Cost per Available Seat Mile (CASM): Total cost of flying a certain mission including the capital costs.
  - Acquisition Cost: Initial transaction price to obtain the aircraft. These values will provide the primitives for the IO model. Many airlines lease the aircraft therefore only incur a mission capital cost, or receive depreciation costs if the aircraft is actually owned.
  - Cash Operating Cost (COC): Cost of flying a certain mission excluding the capital costs.
  - Total Trip Cost: Total cost of a mission including capital costs

Direct Operating Cost (DOC) is the operational expense that can completely be attributed to the flight in consideration. Due to different sizes and stage lengths of missions, Cost per Available Seat Mile (CASM) is usually considered to be a more meaningful metric. However, due to the inefficiencies within takeoff and landing and other issues related to flight mechanics and fixed costs, CASM usually decreases with distance. Therefore, it is essential to use CASM with attention and make additional effort to use it to compare similar aircraft performing similar missions in similar configurations.

$$CASM = \frac{DOC}{ASM} \quad (22)$$

CASM can be used not only to compare the operating efficiencies of different airlines on the cost side but also can be used for airlines to assess a potentially new airplane purchase.

Table 23: Total Operating Expenses in Q4 2015 for US Airlines [1]

Cost Component	% of Operating Expenses
Labor	31.3
Fuel	16.3
Aircraft Rents and Ownership	7.2
Non-Aircraft Rents and Ownership	4.6
Professional Services	8.7
Food & Beverage	1.7
Landing Fees	2.0
Maintenance Material	1.6
Aircraft Insurance	0.1
Non-Aircraft Insurance	0.2
Passenger Commissions	0.8
Communication	0.9
Advertising & Promotion	0.9
Utilities & Office Supplies	0.7
Transport-related per Regional Carrier	12.6
Employee Business	2.0
Other Operating Costs	8.4

We need to quantify and understand the mechanics of those purchase decisions in order to assess the market performance of the hypothetical family design. For the 4th quarter of 2015, Airlines for America's study of total operating expense build-up for US Airlines are presented in Table 23 [1].

Since Table 23 is an overall average breakdown of entire set of airline operations in US, it is important to note that these percentages are subject to change greatly based on specific operations. However, it is important to highlight that despite relatively low fuel costs of Q4 2015, fuel cost still is a very significant component of an airline operating cost. Labor cost, the biggest component in this breakdown, consists of wages, payroll taxes and employee benefits of general management, flight personnel, maintenance labor, and aircraft and traffic handling personnel. Aircraft rents and ownership, another important element, is the cost of aircraft rentals, depreciation, and amortization of flight equipment including airframes and parts, capital leases, and other flight equipment. In this section, a market share model is explored so that:

$$q_{itt} = M_t * MS_{itt} \quad (23)$$

where

$q_{it}$  is the quantity demanded for product  $l$  of firm  $i$  at time  $t$

$M_t$  is the size of the market at time  $t$

$MS_{it}$  is the market share of the product  $l$  of firm  $i$  at time  $t$

For the narrow-body market, due to the similarity of products, it can be assumed that the fixed operating costs to be very similar between different candidates. For example, it is reasonable to expect the crew costs for the same flight of A319 and B737-700 to be the same. Even though it is possible to expect some significant differences for some components, the majority of the overall impact is caused by labor, fuel, and ownership costs. Therefore, the product differentiation will focus on two main elements: Fuel and therefore the fuel efficiency, ownership costs which is a function of aircraft price.

Estimating the actual fuel burn per hour or per seat is not a straightforward task. Figure 44 shows the fuel burn per hour from 2002 to 2015 for A320 and B737NG families in US domestic operations. It is compiled from US Bureau of Transportation Statistics (BTS) Form 41 Schedule P-5.2. The same dataset also includes other reported statistics such as maintenance and depreciation. The variations in the data are mainly due to different variants and configurations of the planes, different Performance Improvement Packages (PIP), different Origin-Destination pairs and stage-lengths, and perhaps faulty reportings.

Similar to the actual operational fuel consumption, obtaining an estimate of aircraft ownership cost is complicated. Even though both Boeing and Airbus publishes prices annually, almost none of the actual transactions occur at those “list prices”. Order size and company loyalty are some important factors that results in an average discount of about 45% off the list prices [6].

Figures 45,46, and 47 show the historical list prices of the major narrow-body airplanes in this study [158, 85]. Some initial observations are:

- Similar pricing of A320 and B737-800 hints a strong price war especially in the center of the market.

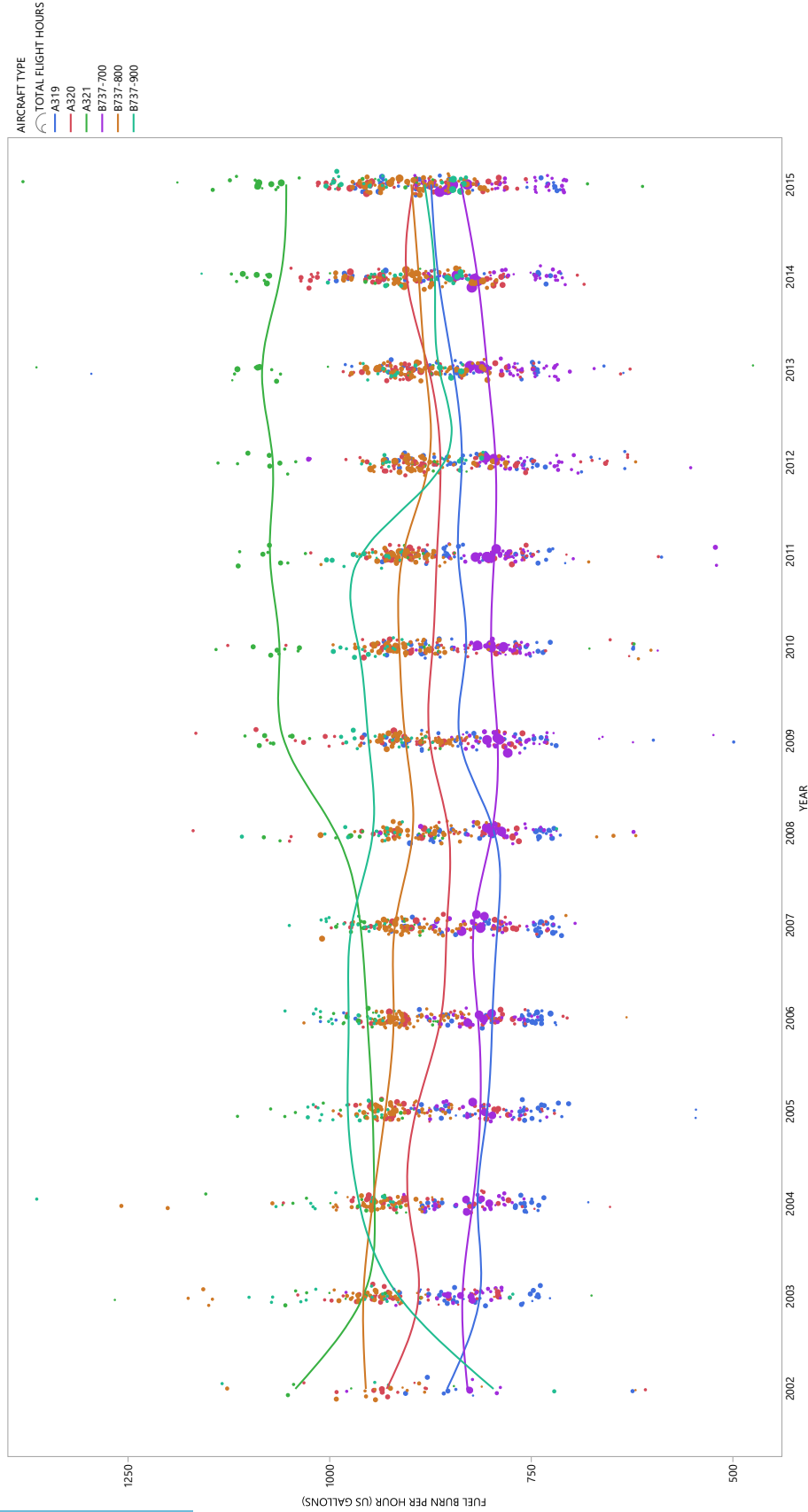


Figure 44: Fuel Burn per Hour for US Domestic Operations between 2002-2015

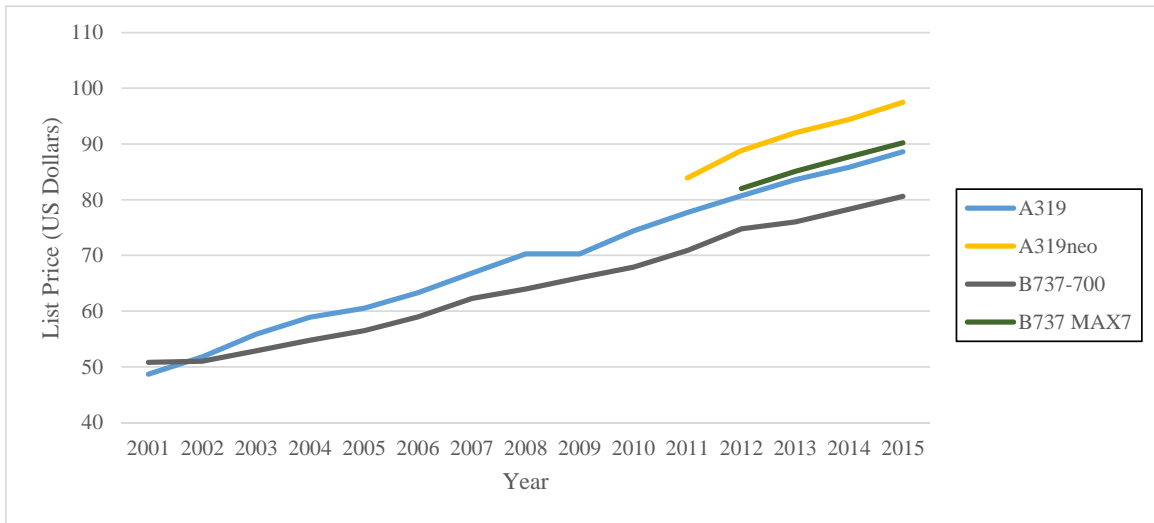


Figure 45: List Price of A319, A319neo, B737-700, and B737 MAX7

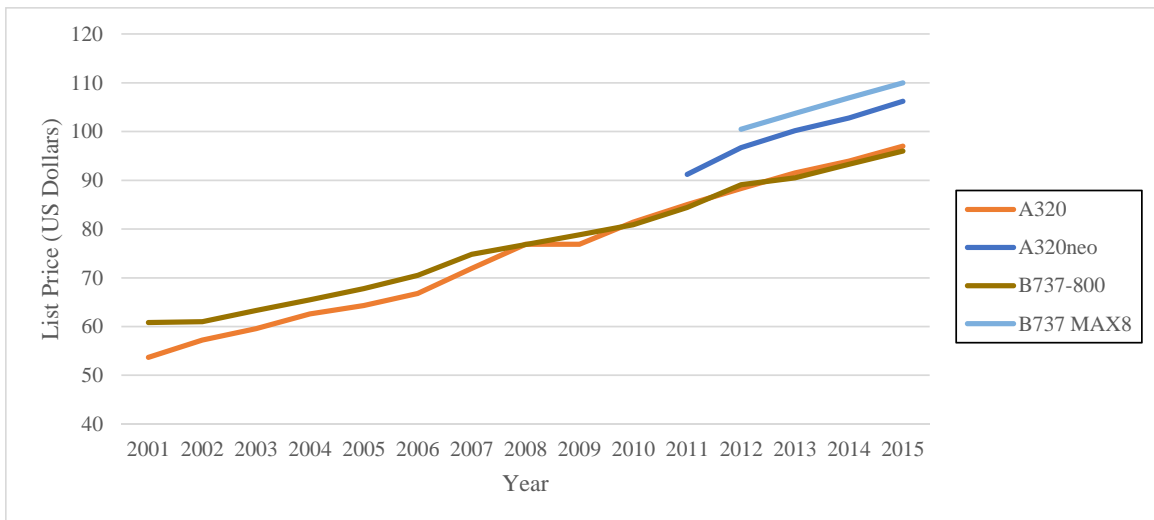


Figure 46: List Price of A320, A320neo, B737-800, and B737 MAX8

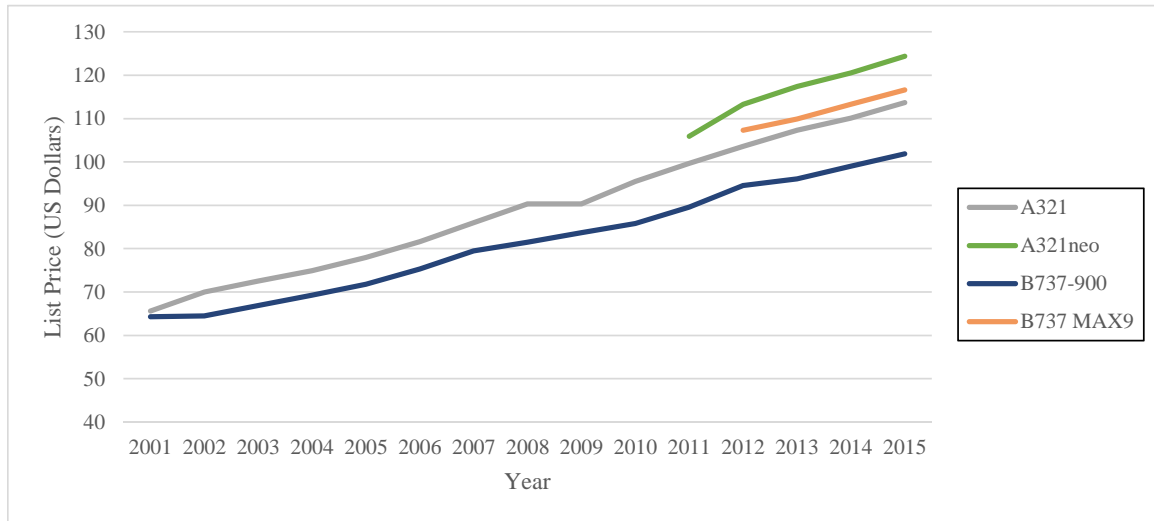


Figure 47: List Price of A321, A321neo, B737-900, and B737 MAX9

- Airbus aircraft tend to be more expensive and yet still gain more market share in the narrow-body market
- New aircraft are priced higher than their predecessors.

In an attempt to bridge the gap between the list prices and the fuel efficiency of similar airplanes, the impact of both on the CASM are estimated. Assuming a monthly lease rate of 0.85% of the 45% discounted prices, an estimation of a block time for a 1060NM mission used of 300 hours of monthly utilization can be used [9]. 660NM could also be a useful benchmark as a representative distance between Atlanta and Newark airports. Another 8.5% can also be added as an insurance cost as a function of the capital costs. For the fuel burn cost, the total fuel consumption for the mission are simply multiplied by the jet fuel price of the corresponding year. Finally, since CASM depends heavily on the number of seats while the stage length is fixed, T100 data is used to estimate the mean number of seats as of 2015 for the existing narrow-body aircraft. Although, a 2-class typical seating is a good enough assumption, the actual number of seats give a better definition of airlines' understanding of CASM. The average seats for A320s are 130.4, 152.6, and 181.7 while it is 140.7, 162.6, and 175.2 for competing Boeings.

Table 24: Market Share vs VCASM

Segment	A320neo Orders	B737 MAX Orders	Market Share	VCASM Ratio
NB-I	50	60	0.54	0.920
NB-II	3327	2795	0.45	1.015
NB-III	1094	217	0.16	1.0234

Using the values presented in Table 24, a simple measure of sensitivity to both aircraft price and fuel cost is obtained. When the slope calculation is weighted by the number of orders, the sensitivity is found to be -8.06224. These results are highly comparable to the own price elasticities obtained by Keefe for the narrow-body market even though the author has used delivery data with 1 and 2 year lags [114]. Considering the delivery lead time in the industry, it is possible to conclude that the estimation is reasonable compared to the literature [103]. Although this approach is quite simple due to lack of detailed panel data, it still captures two major components of value relationship between the airlines and aircraft manufacturers.

$$FCASM_{ilt} = \frac{FB_{il}(\mu_{il}^{miles}) * P_t^{fuel}}{\mu_{il}^{seats} \mu_{il}^{miles}} \quad (24)$$

$$MCCASM_{ilt} = \frac{LP_{ilt} * DR * MLR * MissionBlockTime_{il}(\mu_{il}^{miles})}{\mu_{il}^{seats} \mu_{il}^{miles} * MonthlyUtilization_{il}} \quad (25)$$

$$VCASM_{ilt} = FCASM_{il} + MCCASM_{ilt} \quad (26)$$

$$CASM_{ilt} = VCASM_{ilt} + FXDCASM_{ilt} \quad (27)$$

where

$FCASM_{ilt}$  is the Fuel Cost per Available Seat Mile for product l of firm i at time t

$FB_{il}$  is the Fuel Burn of product l of firm i (a function of  $\mu_{il}^{miles}$ )

$P_t^{fuel}$  is the jet fuel price at time t

$\mu_{il}^{seats}$  is the mean number of seats for product l of firm i

$\mu_{il}^{miles}$  is the mean stage-length for product l of firm i

$MCCASM_{ilt}$  is the Mission Capital Cost per Available Seat Mile for product l of firm i at time t

$LP_{ilt}$  is the List Price of product l of firm i at t

$DR$  is the Discount Rate (Industry Average)

$MLR$  is the Monthly Lease Rate (Industry Average)

$VCASM_{ilt}$  is the major Variable Cost per Available Seat Mile of product l of firm i at time t

$FXDCASM_{ilt}$  is the major Fixed Cost per Available Seat Mile of product l of firm i at time t

$CASM_{ilt}$  is the Cost per Available Seat Mile of product l of firm i at time t

In a market environment such as the narrow-body market, it is possible to have a higher number of explanatory variables to better fit the historical data. Despite introducing more terms to the model, due to the complicated nature of those bargains, lack of publicly available data and “closed-door” discussions, and airline-specific needs, there is not a single model in the literature that stands out as a reliable explanation. For example, Southwest favors Boeing aircraft due to fleet commonality and Boeing awards their customer loyalty. In 2011, Southwest ordered 150+150 option 737 MAXs for around \$35m USD per frame that corresponds to about 65% discount [6]. Such real-world phenomena such as the bias towards a certain company are hard to quantify. The focus was solely on coming up with a reasonable technique to award fuel-efficient designs and competitive pricing with higher market-share. This simple market share model will enable us demonstrate the capabilities of the IO model. Once the demand evolution is obtained and the state of the market at each time period can be observed by the players, the quantity demanded is simply the market share multiplied by the overall demand. These simulations to be performed are in fact counterfactual experiments using empirical data obtained from the history of the industry. It is natural to expect some discrepancies in such simulations. Especially for the LCA market, which is a big and complex environment with many factors affecting the outcome, the simulation results should not be expected to perfectly match the reality. However,



this methodology is intended to provide a comprehensive and transparent framework for forward-thinking, top-level decision makers.

### 5.4.3 Spatial Utility Bertrand Competition

Even though the sensitivity of demand to some of the major factors in the industry are estimated, there is still a need for a discrete choice model that can be used in a simulation environment. In many markets, most of the time, consumers are not allowed to pick their “ideal product” due to the discrete amount of products offered by firms. In this thesis, it is assumed that the customers’ decision when picking a product are influenced by these factors:

- The “quality” of the product vs others
- The price of the product vs others
- The difference between the customer’s ideal product and the product vs others
- How much the customer is willing to deviate from their original target

The demand model in this thesis is a spatial utility model built on the work of Aguirregabiria and Vicentini which is an enhancement of De Palma’s work [30, 33]. The enhancements are mainly in allowing different quality values from different firms as well as expanding the market to two dimensions. On a two-dimensional market space, at every period  $t$ , for each consumer at location  $z$ , utility for the product  $l$  of firm  $i$  can be formulated as:

$$u_{ilt} = \omega_{il} - p_{ilt} - \tau \|z - z_l\| + v_{il} \quad (28)$$

where

$u_{ilt}$  is the indirect utility of consumer at location  $z$  for the product of firm  $i$  at location  $l$

$\omega_{il}$  is the quality of product of firm  $i$  at location  $l$

$p_{ilt}$  is the price of the product of firm  $i$  at location  $l$  at time  $t$

$\tau$  is the unit transportation cost

$z$  is the location of the consumer

$z_l$  is the location of the segment  $l$

$v_{il}$  is the idiosyncratic preference of the customer for product of firm  $i$  at location  $l$

Assuming  $v$  is independent of  $z$  and has a type 1 extreme value distribution, and integrating Equation 28 over  $v$ , the local demand for product of firm  $i$  at location  $l$  can be formulated as:

$$\sigma_{il}(z, n_t, p_t) = \frac{n_{ilt} \exp\{(\omega_{il} - p_{ilt} - \tau \|z - z_l\|)/\mu\}}{1 + \sum_{i'=1}^I \sum_{l'=1}^L n_{i'l't} \exp\{(\omega_{i'l'} - p_{i'l't} - \tau \|z - z_{l'}\|)/\mu\}} \quad (29)$$

where

$n_t$  is the market structure at time  $t$

$\omega_{il}$  is the quality of product of firm  $i$  at location  $l$

$\mu$  is the dispersion parameter

Finally, integrating Equation 29 over the distribution of customers  $z$ , the total demand for the product of firm  $i$  at location  $l$  at time  $t$  can be obtained:

$$s_{il}(n_t, p_t, \phi_t) = \int_C \phi_t(dz) \sigma_{il}(z, n_t, p_t) \quad (30)$$

Dispersion parameter  $\mu$  helps model the impact of non-spatial horizontal product differentiation. On the other hand, as the transportation cost parameter  $\tau$  increases, it will make customers less willing to deviate from their original positions.

There is an abundance of different discrete choice models in the literature to choose from. However, a spatial utility model will provide certain benefits specifically to a family design problem. In such problems, the designs should be sufficiently close to each other so that the commonality can be utilized. At the same time, they should be different enough

from each other so in the end, the result is a product positioning problem. Adaptation of spatial logic to the design space enables a direct representation of such cross elasticities and perhaps more extensive product positioning assessments.

Sub-game equilibrium is chosen to be a Bertrand price competition. This stage is a game of complete information where the firm  $i$ 's profit-maximizing decision can be shown as the First-Order Condition (FOC) for each of its prices as:

$$s_{ilt} + (p_{ilt} - c_{ilt}) \frac{\partial s_{ilt}}{\partial p_{ilt}} + \sum_{v \neq l} (p_{iv't} - c_{iv't}) \frac{\partial s_{iv't}}{\partial p_{ilt}} = 0 \quad (31)$$

where the variable profit function  $R_{it}$  is defined as:

$$R_{it}(n, p, \phi) = \sum_{l=1}^L (p_{ilt} - c_{ilt}) s_{il}(n_t, p_t, \phi_t) \quad (32)$$

This type of an equilibrium will ensure that multi-product firms maximize the overall profit of their portfolio and avoid threatening other designs of theirs by aggressive pricing at certain locations. This sub-game equilibrium can be obtained directly and is independent of the dynamic game as it is static. Therefore, it can be obtained for all states and used as an "input" to the dynamic game. The equilibrium may not be unique, in those cases, the lowest price will be selected.

The solution algorithm is initialized at the marginal costs. In the second step, aggregate demands and partial derivatives are estimated. The main step for the solution follows Gauss-Seidel iteration where each firm picks their best responses turn by turn.

## CHAPTER VI

### EXPERIMENTS

In this Chapter, using the **Case IIA** example, the focus will be on an example problem of two incumbents and an entrant. The state transition probability matrices will be generated to be fed into Monte Carlo Simulations. Results will include distributions of NPV for the entrant as well as the steady-state market structure at the equilibrium.

#### 1. Market Segmentation

- (a) Market Uncertainty-Evolution of Demand
- (b) Demand Model

#### 2. Identify Players and Firm-specific Dynamics

- (a) Incumbents (with observable designs)
- (b) Entrants (with changing designs)

#### 3. Identify Common Platforms

- (a) Identify Critical Design Variables
  - i. Identify Constraints on Design Variables
- (b) Generate Candidate Family Platform Designs
- (c) Generate Performance and Cost Data for Candidate Family Members
  - i. Identify Performance/Cost Constraints
  - ii. Screen for Performance/Cost Constraints

#### 4. Market Simulations

- (a) Industrial Organization

- (b) Monte Carlo Simulations
- (c) Obtain Distributions of Program Value

## 5. Platform Optimization

- (a) Pick value-maximizing platform design
  - i. One-step solution for one entrant
  - ii. Sequential Nash Equilibrium Solution for two or more entrants

### 6.1 Scenarios

For the sake of simplicity, the case study is limited to **Case IIA** where we only have one entrant firm. In this section, different directions of counter-factual experiments that can be conducted on the framework are presented.

***Scenario 1:** How can the incumbent firms prevent new entries, or minimize the market share loss caused by additional competition? How does the anticipation of a potential market entrant influence the decisions of incumbent firm's program managers?*

Richard Aboulafia, an expert in an aerospace advisory firm, states: "Duopolies don't get broken by a new player being aggressive, they get broken because the incumbents become complacent" [5]. Although the narrow-body market is expected to grow to accommodate more firms, similar statements from experts indicate there are certain managerial decisions that can be done by the incumbent firms to make it harder for entrants to realize a profitable program. It is possible to visualize the actions of incumbents in such a case.

***Scenario 2:** Why do firms exit certain segments? What are the main drivers to these decisions?*

As much as entry deterrence strategies are interesting to analyze, it is interesting to analyze product level exits. Sales for both B737-600, and A318 were low and both companies do not replace the smallest sub-segment of narrow-body in the new generation. Numbers as of 2010 indicate that only 79 A318 were delivered compared to 6532 A320s, and only 69 B737-600s compared to 4394 B737-800s. This is an interesting observation as one may wonder what drives these decisions. Possible reasons include:

- Performance constraints
- Firm capabilities
- Competitive analysis
- Risk reduction (including both investment, and technical risks)

Recalling Figure 6, it is possible to argue the performance constraints at the edges of market space become more critical. This doesn't necessarily mean those vehicles can't perform the given design missions, but are not competitive in means of price, or efficiency. In fact, within this framework, the way flexibility is handled is through competitive advantage over the rival designs by performing the given missions better. Firms won't be allowed to enter a sub-segment if the platform design is not suitable to meet the mission requirements, and the regulatory constraints.

**Scenario 3:** *If an entrant firm offers only one independent design that is optimized for the given sub-segment instead of a family of products, what are effective strategies to compete against firms offering families of products?*

In this scenario, the entrant has a single design versus a family of designs. The advantages of a single-product entrant are:

- Reduced entry cost
- Vehicle can be optimized only for one segment
- Increasing the competition in a segment may decrease the prices, and steal demand from other segments.

Similar approach is followed by COMAC and partially by Bombardier as explained in Section 3.6

**Scenario 4:** *How does the competition affect the total CO<sub>2</sub> emissions when two firm total fuel burn is compared to a three firm total fuel burn?*

In the commercial aviation, one of the interesting issues is the effect of competition on the environment. In this scenario, the intent is to compare a duopoly case to a triopoly

Table 25: NASA Goals for System Level Metrics [163]

CORNERS OF THE TRADE SPACE	N+2 = 2020 Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 = 2025 Technology Benefits
Noise (cum below Stage 4)	-42 dB	-71 dB
LTO NO <sub>x</sub> Emissions (below CAEP 6)	-75%	better than -75%
<b>Performance: Aircraft Fuel Burn</b>	<b>-50%</b>	<b>better than -70%</b>
Performance: Field Length	-50%	Exploit metro-plex concepts

case, to identify, and quantify the change in the total CO<sub>2</sub> emissions between different types of competitions.

This study is motivated by the NASA's Environmentally Responsible Aviation (ERA) project goals. There have been studies on vehicle level technology improvements, obtaining fleet level metrics, and different concepts towards this goal [163]. However, competition, a reality of the commercial aircraft market is not considered. One possible result is that the fuel prices may increase the value of efficient aircraft, therefore still decrease the system level fuel burn despite the competition.

***Scenario 5 (This Study): Can this framework be used as a technology valuation tool?***

One possible way to handle the scenario suggested in Case Study 5 is through the modification of the cost elements shown in Figure 29. A new technology program would likely:

- Increase the R&D cost
- Increase the product performance, therefore market performance, resulting in a higher revenue

Framework can handle higher, and uncertain levels of R&D cost, and this can be mapped on the change in the program value distribution. Such a tool would enable top-level decision makers to identify key technologic improvements early on in the design phase, and utilize

the corresponding competitive advantage.

In this section, five case studies to test the capabilities of the proposed framework were suggested. Although some of these case studies need extensive effort to simulate, it would help validate the proposed framework's extension capabilities to account for various scenarios under uncertainty and competition. The focus is on Scenario 5, which as a part of the design problem, is thought to be interesting.

### 6.1.1 Benchmarking-Testing the Hypothesis

**Hypothesis:** *Considering the dynamic, stochastic, competitive, and flexible nature of aircraft family programs, combining an Ericson Pakes class Industrial Organization model of dynamic oligopoly with Monte Carlo Simulations enables the designer to make risk-informed, value-driven platform design decisions in the conceptual design phase.*

To test and quantify the hypothesis, there is also a need for a benchmark and an experimental setup. For this purpose, the following design techniques are initially considered:

- TOGW minimizing/Family TOGW minimizing
- OEW minimizing/Family OEW minimizing
- Fuel Weight minimizing/Family OEW minimizing

Without a doubt, although simple and static, these techniques have traditionally provided important insights to both commercial and military aircraft designers. Even from a marketing perspective, it is possible to argue that these designs will be quite competitive. However, to measure the real value, they should be tested when the market is uncertain and competitors can react. Weight-focused methods do not directly translate to economic success. A fuel burn optimized wing can be shrunk to cost less in means of development and manufacturing in expense of additional fuel cost. Eventually, under certain conditions, that may be a more profitable design. These enhanced definitions form the main focus in this thesis.

In the field of strategic decision making at firm-level for market success, the most basic, simple, and popular technique is the standard Net Present Value (NPV) method. Therefore the primary benchmark is NPV. Standard Net Present Value methods provide static,



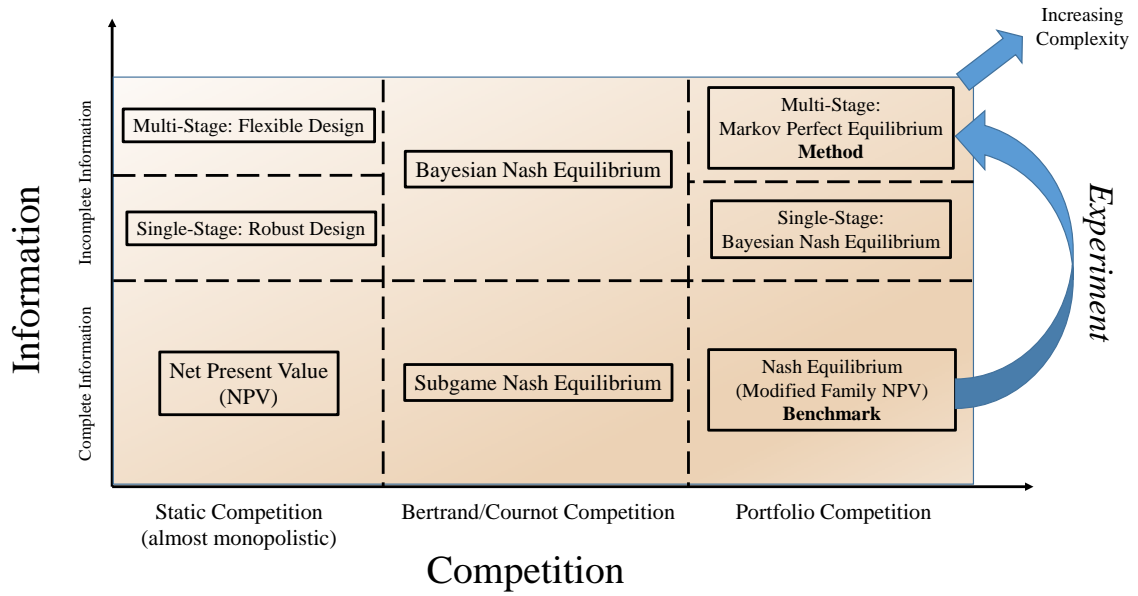


Figure 48: Experimental Plan and Related Methods

deterministic, and one-shot valuations in a sense that they ignore competition, uncertainty, and managerial flexibility of aircraft family programs. That being said, the traditional NPV method doesn't take into consideration the active management of the firm in real-time to market and firm level shocks. In this context, NPV refers to the technique and not the value metric used for program success. When the uncertainty grows, the strategic control elements firms can utilize to adapt to the environment is not considered in NPV. For the competition case, a program is almost certainly expected to lose value when not responded to competitive reactions. Even when the program managers react to competitors' actions, competitive market simulations will yield a more "realistic" but perhaps a lower program turnover value. Due to all these potential aircraft program valuation discrepancies, there is a need to create a common type of market analysis to test different designs on a consistent platform. That gap is in fact filled by the VDD paradigm which have been extended to include different elements usually neglecting the active managerial actions throughout the projects.

In Figure 48, a categorization of the analytical tools used in the design-for-market approaches is displayed. A substantial amount of effort has been put specifically to robust

design methodologies to design products that are successful in uncertain market conditions. As displayed in Figure 11, flexible design approaches are useful when the requirements in the market are also subject to change. As the competition becomes critical in market systems, difficulty arises. Under complete information, such competitive methods are usually assessed by solving Nash Equilibria. When the actions of the competitors are not known, players have to form beliefs about the uncertain elements. These approaches are investigated with Bayesian methods. Both static competition and Bertrand/Cournot competition methods traditionally focus on single product designs where the number or variety of the products offered is out of question. Because of this, product family optimization problems fall within the domains of product portfolio optimization. In the case of competition, they are grouped within the “portfolio competition”.

The approach to test the hypothesis using the methodology introduced in Chapter 4 is comparative assessment. The next section describes the newly created benchmark method that keeps certain attributes of traditional NPV methods such as static and deterministic considerations but expands it to a portfolio optimization in a competitive approach. Creation of a new benchmark method was motivated by the lack of a suitable methodology for product families which the result from MPE can be compared to.

#### 6.1.1.1 Static, Deterministic, and Competitive NPV

The competition between product families is a game played in a multi-firm, multi-product environment. Firms use their product platforms as means of exploring derivative options once invested in the market. This investment is denoted by  $MEC_i$ , this cost is incurred at  $t=0$ . In this version of deterministic NPV, firms, knowing that they are already in the market, decide at  $t=1$  for the segments to enter and pay the Segment Entry Cost  $SEC_{i,l}$ . No entry or exit happens after  $t=1$  as there is no flexibility involved. Action or portfolio selection of firm  $i$  is  $a_i$  and  $a_i^*$  is the best response for the firm  $i$ .

$$NPV_i = -MEC_i + \sum_{t=1}^T \beta^t \pi_i(a_i, a_{-i}; x) \quad (33)$$

where similar to the notation in literature [29]:

$$\pi_i(a_i, a_{-i}; x) = R_i^*(a_i, a_{-i}; x) - SEC_{il}(a_i) \quad (34)$$

where the revenue of firm  $i$ ,  $R_i$ , at the Bertrand-Nash equilibrium for products  $l$  can be written as:

$$R_i^*(a_i, a_{-i}; x) = \sum_{l=1}^L a_{il} [p_i^*(l, a_{-i}, x) - c_{il}] q_i^*(l, a_{-i}, x) \quad (35)$$

Following these notations, for a static, one-shot game of complete information the Nash Equilibrium for the segment-level entry problem satisfies:

$$\pi_i(a_i^*, a_{-i}^*; x) \geq \pi_i(a_i, a_{-i}^*; x) \quad (36)$$

When the firms can observe both the competitors actions  $a_{-i}$ , the marginal costs, and other firm qualities of all the players  $x$ , they can see each others' best responses. NPV distribution resulting from the game simulation may, or may not yield higher value than this deterministic result. In both cases though, the same Spatial Bertrand Competition model that solves the static market equilibrium at the sub-game level is used.

In the example scenario, there are three players with 8 strategies each resulting in a 8x8x8 game. Such games are highly vulnerable to having more than one Nash Equilibrium. This is a very common problem in these types of games and different methods exist to “pick” among alternates. It is visually demonstrated that for the high demand market scenario that there is a single equilibrium and that is when all firms are present in the market with all their product line. That combination will be picked as the equilibrium product portfolio.

### 6.1.2 Computation of MPE

As a response to the existing valuation technique of a product family, this valuation involves solving a multi-stage, multi-firm, multi-product game of incomplete information with exogenous uncertainty in which the firms have to form beliefs about other players' actions. This dynamic, discrete game follows Aguirregabiria and Vicentini's method which follows Aguirregabiria and Mira to represent a MPE as a fixed point in a space of choice probabilities is utilized [30, 28]. First, Conditional Choice Probability  $P^a$  (CCP) is defined as:

$$P^\alpha \equiv \left\{ P_i^\alpha(a_{it}|n_t) : i \in I; a_{it} \in A; n_t \in \{0, 1\}^{IL} \right\} \quad (37)$$

So that, with the distribution function  $G_i(\cdot)$ :

$$P_i^\alpha(a_{it}|n_t) \equiv Pr(\alpha_i(n_t, \varepsilon_{it}) = a_{it}|n_t) = \int 1 \{a_i(n_t, \varepsilon_{it}) = a_{it}\} dG_i(\varepsilon_{it}) \quad (38)$$

Integrated Bellman equation for  $V_i^\alpha(n_t)$  can be written as:

$$V_i^\alpha(n_t) = \int \max_{a_{it}} \left\{ \pi_i(a_{it}, n_t) + \varepsilon_{it}(a_{it}) + \beta \sum_{a_{-it}} V_i^\alpha(n_t + 1[a_{it}, a_{-it}]) \left[ \prod_{j \neq 1} P_j^\alpha(a_{jt}|n_t) \right] \right\} dG_i(\varepsilon_{it}) \quad (39)$$

Integrated Bellman  $v$  equation uses choice specific value functions  $v_i^P(a_{it}, n_t)$ :

$$v_i^P(a_{it}, t) = \pi_i(a_{it}, n_t) + \varepsilon_{it}(a_{it}) + \beta \sum_{a_{-it}} V_i^\alpha(n_t + 1[a_{it}, a_{-it}]) \left[ \prod_{j \neq 1} P_j^\alpha(a_{jt}|n_t) \right] \quad (40)$$

Therefore mapping of CCPs into CCPs can be written as:

$$\psi_i(a_{it}|n_t, P) \equiv \int 1 \left\{ a_{it} = \arg \max \left\{ v_i^P(a, n_t) + \varepsilon_{it}(a) \right\} \right\} dG_i(\varepsilon_{it}) \quad (41)$$

Best response probability function  $\psi_i$  provides the probability that a certain action is the best response of the firm given the state of the market and other firms behave according to their choice probabilities. Under the assumption that the private information shocks  $\varepsilon_{it}(a)$  are independently and identically distributed (iid) with type 1 extreme value distribution, the best response probability function becomes:

$$\psi_i(a_{it}|n_t, P) \equiv \frac{\exp \left\{ v_i^P(a_{it}, n_t) \right\}}{\sum_{a \in A(n_{it})} \exp \left\{ v_i^P(a, n_t) \right\}} \quad (42)$$

Since firm  $i$ 's best response function is:

$$\alpha_i^{BR}(n_t, \varepsilon_{it}, a_{-i}) = \arg \max \left\{ v_i^P(a_{it}, n_t) + \varepsilon_{it}(a_{it}) \right\} \quad (43)$$

MPE is a set of strategy functions such that each firm maximizes their value functions given other firms' strategies. Mathematically, this can be written as:

$$\alpha_i^*(n_t, \varepsilon_{it}) = \alpha_i^{BR}(n_t, \varepsilon_{it}, a_{-i}^*) \quad (44)$$

Equation 42 is much easier to solve at the expense of a specific type of shock distribution. Even for the simplified 3-player, 3-products situation, this assumption makes simulations practical and computationally fast. In addition, the realistic assumption of opening and closing a maximum of one store per period forms a sparse matrix that reduces the number of iterations. For certain industries, this assumption would be limiting. However, for the aircraft industry, it is very difficult to develop multiple derivatives in a single year, which corresponds to one period of time in these simulations.

Computation of MPE is also solved by using Gauss-Seidel iterations over the best response functions. The solution stops with an initialization of the vector of probabilities which is followed by value function iterations on the Bellman equation. Using the converged value functions, Gauss-Seidel iteration is followed by solving best responses for first firm, then second firm etc. in a turn by turn fashion until the values converge within a certain threshold.

#### 6.1.2.1 *Curse of Dimensionality*

DP approaches are vulnerable to “curse of dimensionality” when the computational burden of calculating possible future outcomes increase exponentially along the number of state variables. This greatly limits the number of firms that can be incorporated into the model [56]. In certain cases continuous-time modeling may have advantages to discrete-time models in computational efficiency [70]. However, EP model is widely used with discrete-time approaches. LCA Industry has only a few firms which allows the users of this simulation environment to test multiple scenarios fast. Despite this, there are still ways to make computations faster:

1. Reduce the number of levels in the action space
2. Define state space so that any recently calculated continuous state variable is rounded up, or down to a discretized setting.

IO models offer tremendous capabilities over the simplified models of game theory, and ROA at the expense of computation burden. To use these benefits, strategy space should be intelligently limited. Size of the state space for the original plan was to include

- Market Demand Structures (M)
- Experience Level (E)
- Designs (L)
- Number of Firms (I)

For example, size of the state space would then be  $M \times 2^{(E \times I \times L)}$  which would correspond to  $\approx 10^{14}$  combinations for a triopoly with three products and five experience states on five market structures. Instead, the assumption related to LRMC is used to avoid using the experience state. The new state space size then becomes 2560 which is manageable. This reduction should be made to enable successive iterations on the design on a fast MPE computation.

Computational speed for the three market types, three firms with three potential products ranged between 50 minutes to 80 minutes on an average computer. This computation also includes the estimation of the static equilibria of the spatial Bertrand subgame for all 1536 combinations. However, this part is only a small fraction of the overall computation ranging from 3 to 4 minutes. Considering it takes FLOPS/ALCCA about a second to run each individual vehicle and therefore about 3 seconds for a 3 derivative family, bottleneck of the computations introduced in the methodology is the dynamic game. These speed issues drive the state space reduction explained in this section.

## ***6.2 Narrow-Body Example (Case IIA)***

### **6.2.1 Incumbents**

Apart from having a fixed design, the incumbent firms, just as the entrants, decide on prices of their products as well as their product lines via entry/exit decisions. The framework could allow for more than two incumbents, but we avoid this for several reasons. First, there are not many dominant players in the narrow-body market as of 2016. Second, the complexity

Table 26: Incumbent Firms' Unique Properties

Design Variable	Firm A	Firm B
Wing Area (ft <sup>2</sup> )	1320	1380
Wing Taper Ratio	0.18	0.22
Wing Thickness-to-Chord Ratio	0.13	0.15
Wing Sweep Angle (deg)	24	26
Wing Aspect Ratio	10.45	10
Horizontal Tail Area (ft <sup>2</sup> )	335.8	367.0
Vertical Tail Area (ft <sup>2</sup> )	268.7	293.6
Induced Drag Relative to Baseline	-5%	0
Parasite Drag Relative to Baseline	+2%	0
Wing Weight Relative to Baseline	+5%	0
Development Cost Relative to Baseline	+3%	0
Manufacturing Cost Relative to Baseline	+3%	0

Table 27: Economical and Technical Performance of Incumbent Firms

Response	Firm	NB-I	NB-II	NB-III
Fuel Burn (lbs) (For a 1060NM mission)	Firm A	12030	14155	16452
	Firm B	12422	14503	16826
Independent Development Cost (million US Dollars)	Firm A	11785	12646	13511
	Firm B	11562	12406	13243
Marginal Cost @ 2000 units (million US Dollars)	Firm A	55.51	60.89	66.13
	Firm B	54.64	59.80	64.96
Marginal Cost @ 4000 units (million US Dollars)	Firm A	51.15	55.96	60.78
	Firm B	50.35	55.03	59.70

of identifying a MPE increases exponentially as more firms are introduced. Third, it is questionable if the market can sustain too many players and finally even only a few number of “static”, incumbent firms are enough to demonstrate the methodology.

Incumbent designs in this case study are not necessarily optimized designs. They are also not representations of any actual vehicles in the industry and do not reflect a certain year technology level. The reason they are picked to be slightly different is to demonstrate the capability of the framework to handle heterogeneous and substitutable goods. As incumbents are unable to make design changes, the next step is to estimate the economical and technical performance of the entire family for both Firm A and B. These values will provide the primitives for the IO model and stay the same as trade studies are conducted for the entrant Firm C. Table 27 presents these results.

Table 28: Technology Impact Matrix (TIM) of Notional Technologies

Technology Impact	Composite Fuselage (T1)	Composite Wing (T2)	Laminar Flow (T3)
Wing Weight		-20%	
Fuselage Weight	-25%		
Induced Drag		-2%	-10%
Profile Drag	-2%	-2%	-5%
R&D Cost	+2%	+4%	+15%
Manufacturing Cost	+10%	+6%	

### 6.2.2 Entrant Design Alternatives

As explained in Section 5.2, the design problem for the case study was simplified into selecting a certain technology in an “on and off” style. For this reason, first, a baseline design for the entrant (Firm C) is generated which will be used as a platform for applying different technologies. In Table 28, three technologies are exhibited that will be used in this case study. The assumption is that a firm picks a technology only if it results in a perceived financial success. Including the baseline design, four candidate family designs were generated.

Methods such as Technology Impact Forecasting (TIF) usually deals with estimating potential and usually technical performance benefits of a new technology or a new technology package. On the other hand, in this case study, the focus is on the uncertainty that is caused by the market uncertainty and the competitive reactions. For this reason, if a technology is picked, the technological benefits, such as fuel burn reduction estimation will be assumed to be exact.

Optimization of geometric variables in an aircraft design problem needs models of representative technology levels and available technical information. However, it is possible to expect, in the presence of a technology infusion, for those optimal points to shift. For example, a composites technology that can reduce the weight of the airframe can also decrease the need of a bigger wing. Within this study, the geometries are kept fixed at the conceptual level and are not “re-optimized”.



Table 29: Firm C Baseline Platform Design

Design variable	Firm C
Wing Area (ft <sup>2</sup> )	1350
Wing Taper Ratio	0.2
Wing Thickness-to-Chord Ratio	0.14
Wing Sweep Angle (deg)	25
Wing Aspect Ratio	10.22
Horizontal Tail Area (ft <sup>2</sup> )	351.3
Vertical Tail Area (ft <sup>2</sup> )	281.1

Table 30: Performance of Firm C on Different Technology Scenarios

Response	Technology	NB-I	NB-II	NB-III
Fuel Burn (lbs) (For a 1060NM mission)	T0 (Baseline)	12231	14287	16639
	T1	11600	13500	15636
	T2	11605	13554	15755
	T3	11403	13285	15438
Independent Development Cost (million US Dollars)	T0 (Baseline)	11506	12345	13188
	T1	11432	12243	13062
	T2	11695	12560	13429
	T3	13062	14028	15004
Marginal Cost @ 4000 units (million US Dollars)	T0 (Baseline)	50.01	54.72	59.41
	T1	52.63	57.44	62.26
	T2	51.26	56.18	61.02
	T3	49.39	54.06	58.83

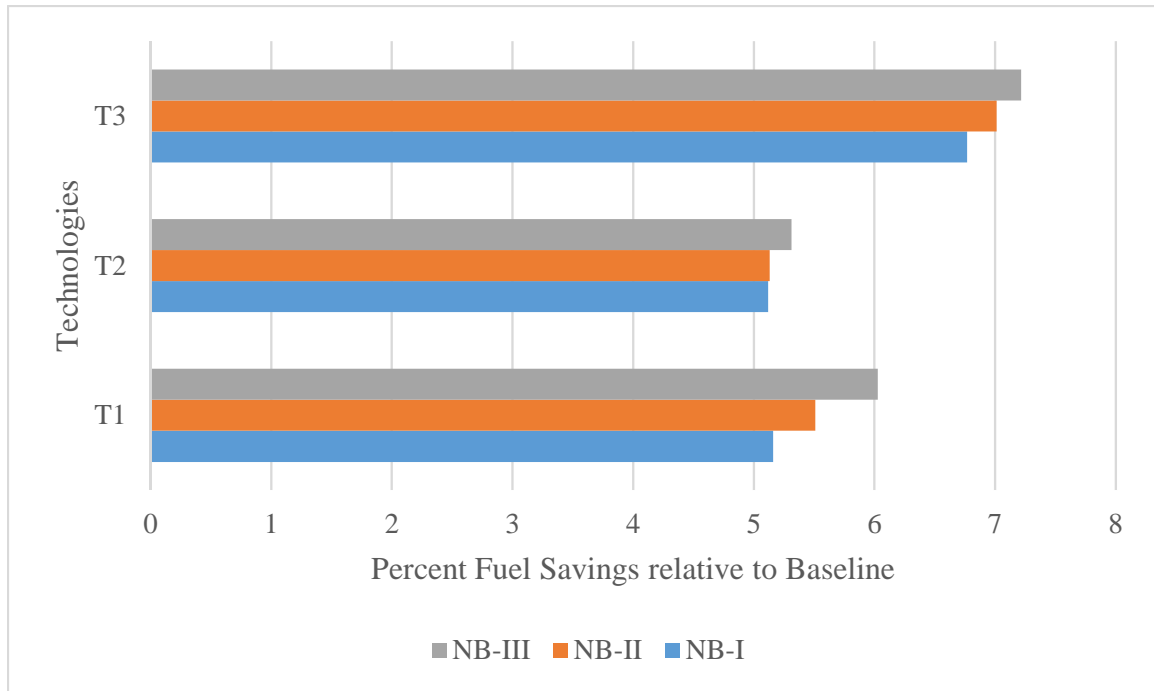


Figure 49: Fuel Savings corresponding to Technologies

A perhaps not surprising result following the technology scenarios is that even though the family members benefit similarly from implementation of a new technology, the NB-III derivative benefits the most. This is due to the well-known impacts of scale effects. In addition, specifically for NB-III, the longest derivative, the benefits of a composite fuselage technology is bigger. This result is found intuitive.

### 6.2.3 Simulation Primitives

The representation power of microeconomic models rely on the quality of cost and demand models. LCA market remains as one of the most difficult areas to model due to high percentages of private-kept data. IO models can be used specifically with estimation techniques which, as long as data is available, allows “reverse-engineering” certain drivers of the industry. In this thesis,

In these simulations, there are three different types of market structures: Low, normal, and high demand scenarios that are all centered at the same location in the market space at  $[0.5,0.5]$ . The coefficients in the utility function are picked as 0.8 for  $\tau$ , 0.07 for  $\mu$ , and in

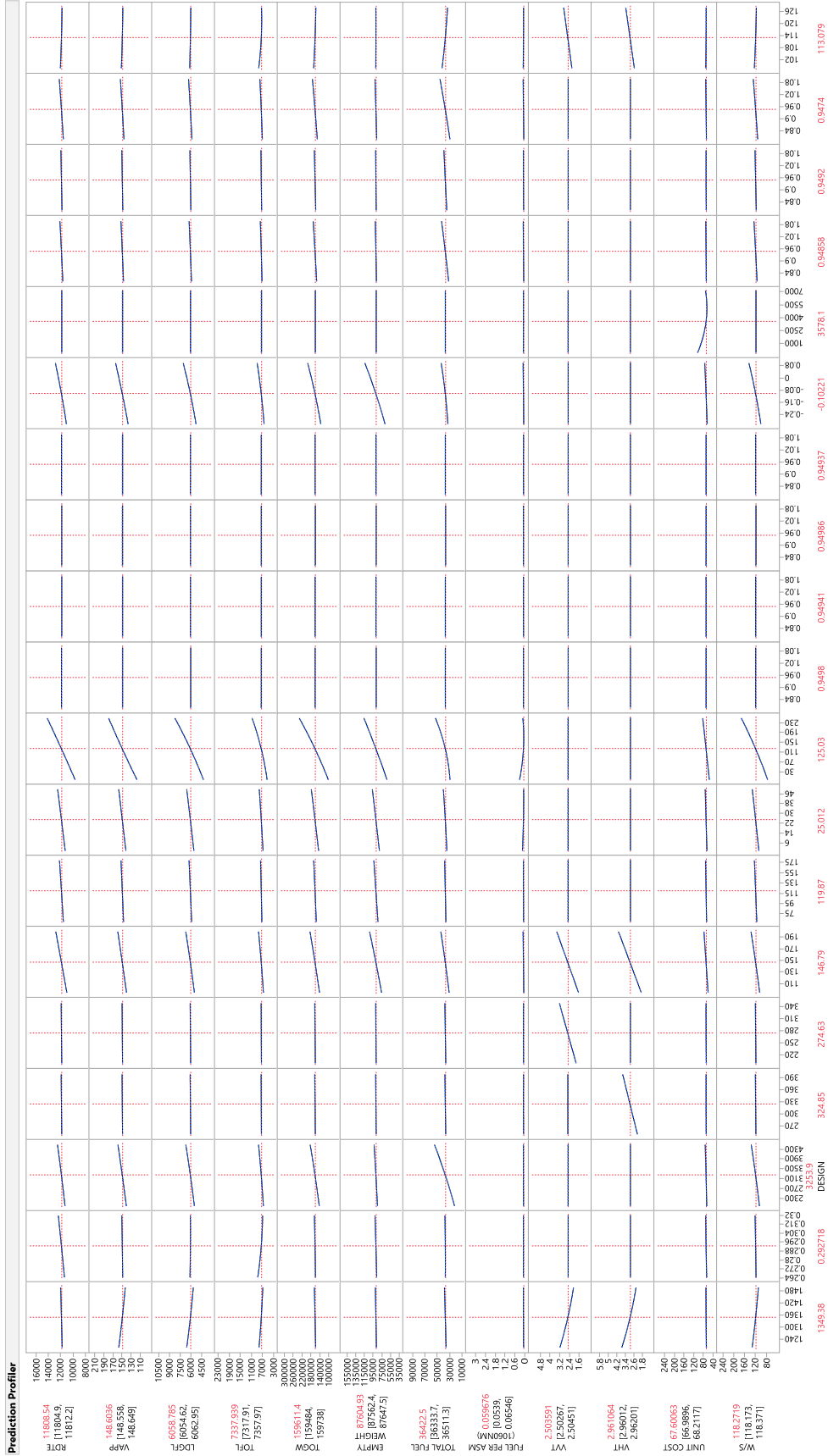


Figure 50: Prediction Profilers for the Hypothetical Narrow-Body Entrant

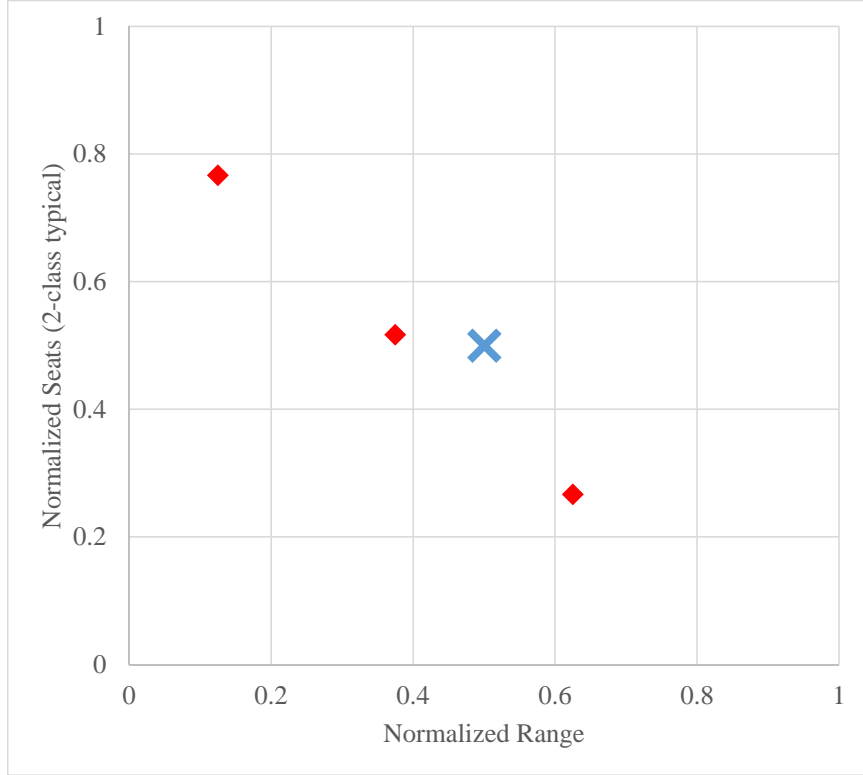


Figure 51: Notional Market Center (Blue Cross) and Example Case Study Locations

addition some outside good with a net utility of 0.1 is assumed to be present. Although it depends on the customer distribution, an example Price Elasticity of Demand (PED) is also presented here in Equation 47. With the assumed coefficients, a trend consistent within different analyses in the literature is obtained. Calibrating such functions and obtaining the coefficients depend on the abundance and quality of panel data. With proper data, there are methods in the literature for estimation of such coefficients for logit models such as Berry Levinshon Pakes [44] (BLP).

$$\Delta M = \begin{pmatrix} 0.4 & 0.4 & 0.2 \\ 0.4 & 0.4 & 0.2 \\ 0.4 & 0.4 & 0.2 \end{pmatrix} \quad (45)$$

$$M = \begin{pmatrix} 1000 \\ 2000 \\ 4000 \end{pmatrix} \quad (46)$$

$$PED_{FirmC-Baseline} = \begin{pmatrix} -8.64 & 0.7573 & 0.1021 \\ 0.1253 & -7.993 & 0.2092 \\ 0.04776 & 0.5915 & -8.406 \end{pmatrix} \quad (47)$$

Quality term  $\omega$  is used as a proxy for the fuel efficiency. As the demand is assumed to increase as the fuel burn for the representative mission drops, this metric is formatted as a value that increases as the fuel efficiency increases. This metric can be considered as a deduction of Fuel Cost per Available Seat-Mile from the Revenue per Available Seat-Mile (*RASM*). Assuming these are the only drivers airlines use for selecting one aircraft over another, the relationship between *FCASM* and *MCASM* presented could imply that the fuel price is a very important exogenous factor. For the simulations that last 20 years, based on the forecast on Figure 25, an average fuel price of \$3/gallon is picked and assumed to be fixed throughout the scenarios.

Results from the solutions of Bertrand-Nash equilibria show markup values around 15%. Firms tend to price more fuel efficient planes higher and the markup values also go up when the competitors don't completely cover the entire market.

Initial state of the market is given as:

$$state = \begin{pmatrix} & \text{FirmC} & & & \text{FirmA} & & & \text{FirmB} & & & \\ \phi_t & NB-I & NB-II & NB-III & NB-I & NB-II & NB-III & NB-I & NB-II & NB-III & \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & \end{pmatrix} \quad (48)$$

The incumbent firms (Firm A and Firm B) are already in the market with the smallest derivative, Firm C is attempting to enter this market. For the entry cost, the high cost scenario is used.

#### 6.2.4 Results

Keeping the same incumbents, a total of 4 technology scenarios are simulated. Once the state transition matrix was obtained from these runs, 1000 Monte Carlo Simulations were run for each scenario resulting in a distribution of NPVs as well as separate discounted cumulative cash flows. Additional visual enhancement was used to show common paths of cash flows. In addition, a distribution of breakeven years is also obtained. Any simulation

Table 31: Program Values Obtained from Different Techniques (USD 100 millions)

Method	T0	T1	T2	T3
NPV	-6.920	1.201	-3.472	26.181
Dynamic Game	-2.152	6.824	1.840	33.958

that doesn't break even within 20 years is considered to be unsuccessful. These numbers are compared to the values that come from the standard NPV method.

For the example problem, it is possible to see that the values are quite comparable. It is also possible to argue that the difference between the values don't fluctuate significantly. This is mainly due to the usage of enhanced method of NPV that takes the weighted market average as well as solving a complete information portfolio problem. Standard NPV method that is used in this comparison also utilizes the same sub-game Bertrand-Nash Equilibrium as the dynamic game approach. In addition, this example problem included relatively favorable market conditions in a sense that the MPE and Nash Equilibria are comparable.

What the standard NPV methods can't perform is inclusion of the real-time decisions. With the assumption of being able to enter one segment at a time, competition, market uncertainty as well as private-information shock, some interesting results are observed. Typically, firms enter "the heart of the market" first. Then, in the next years, it is observed that their choice of segment depends on their product's competitive strength. This indicates that the firms with "lower quality" products are less sure about their value-maximizing strategies. For example, the reactions of the Firm C at different decision epochs are shown in Figures 52, 53, and 54. The primary pick of the Firm C at the second decision epoch is going for the derivative NB-III although there is also some chance of going for the smallest derivative NB-I. On the third epoch, the chance of not doing anything increases as the firm starts questioning whether it is a good option or not to go for 10% of the market. By the time the firm is at the decision epoch 4, it is very likely that a full market coverage has been reached, waiting seems to be the only option. In this scenario, the development cost of NB-I is assumed to be USD 1b whereas the development cost of NB-III is in excess of USD 2b. There is no fixed cost of waiting in this model.

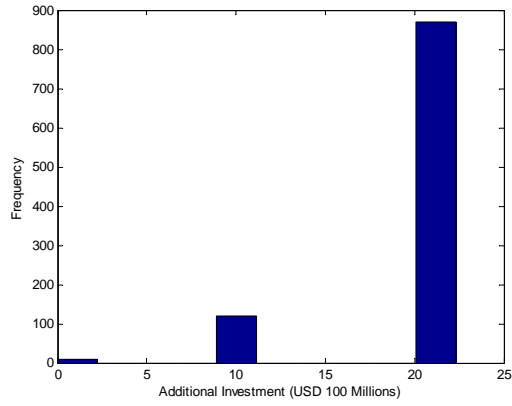


Figure 52: Firm C's behavior at 2nd Decision Epoch (1000 Runs)

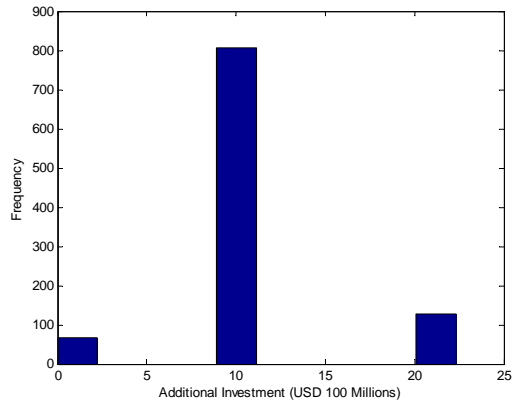


Figure 53: Firm C's behavior at 3rd Decision Epoch (1000 Runs)

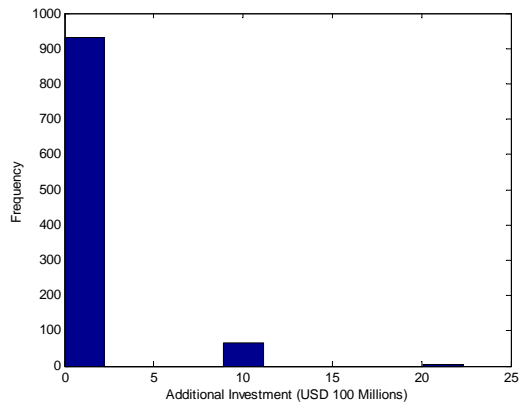


Figure 54: Firm C's behavior at 4th Decision Epoch (1000 Runs)

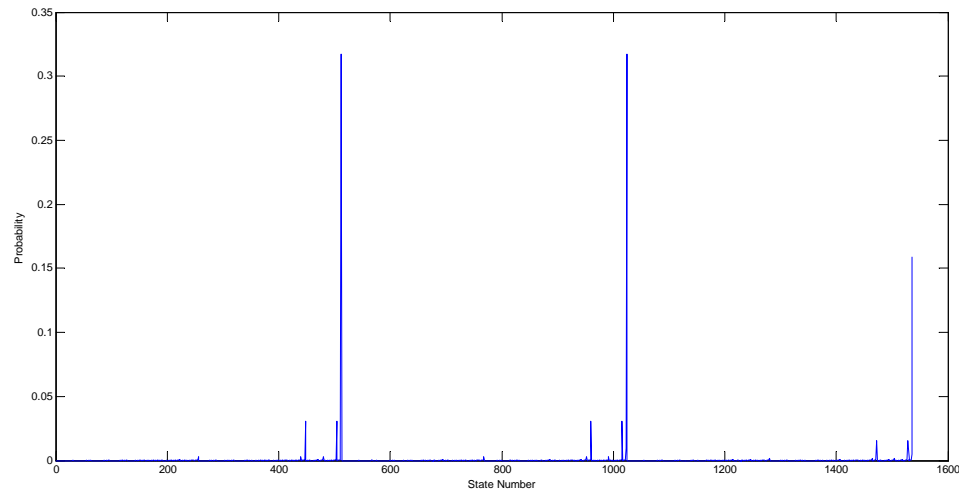


Figure 55: Steady-State Probability Distribution of T0 Scenario

#### 6.2.4.1 Markov Perfect Equilibrium

In Figure 55, the steady-state probability distribution of the market for the T3 Scenario is shown. There are three market structures with  $8 \times 8 \times 8$  states each. It is possible to see from this plot that the most likely outcomes are states 512, 1024, and 1536 indicating cases that all 3 firms are fully present in the market.

In Figure 56, for the high demand T3 Scenario, the payoffs of the firms for all 512 combinations are plotted. Color-coding is also used to indicate the probabilities on the steady-state distribution. Instead of the single, deterministic result of the complete information Nash Equilibrium (shown as the bigger dot). In this part, only the payoffs related to one of the three market scenarios are demonstrated. Due to a combination of perceived market uncertainty, beliefs about competitors' actions, product quality, and entry cost uncertainty, a distribution of probabilities is obtained instead of a single point.

#### 6.2.4.2 Program Risk

There are different measures of risk. Some of them are:

- Breakeven Year
- Total Investment (Sunk Cost)



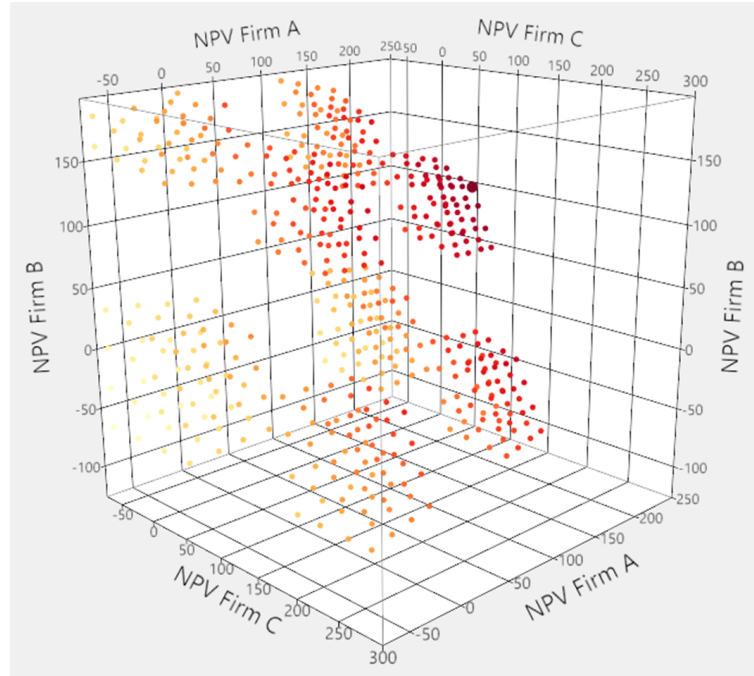


Figure 56: Payoffs for T3 Scenario and High Market Demand

- Volatility of the Returns
- Probability of Making a Loss at the End of the Program

From distributions of DCFs, it is possible to obtain each one of these values. However, the risk is picked to be the probability of the family program making a loss after 20 years in the market. The distribution of breakeven years is also demonstrated.

$$Risk = P(NPV \leq 0) \quad (49)$$

The baseline scenario results in a slightly negative expected value for NPV. The probability of making a loss for Firm C in the baseline technology scenario is 56.2%. The firm can increase the chances of having a successful program to 58.5% by investing in composite fuselage technology T1. The composite wing technology T2 can bring about 49.7% chance of success. Laminar Flow technology T3 seems to be a good investment considering it brings the probability of success to 87.3%.

In Figure 57, the breakeven year distribution is shown assuming a program is a failure if the anticipated returns don't occur within 20 years. Figure 58 presents the distribution

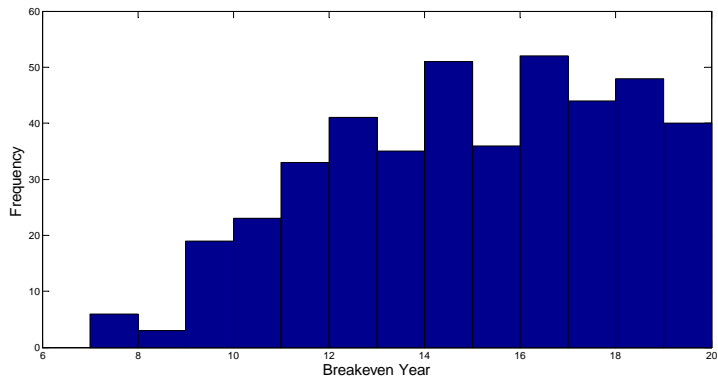


Figure 57: Baseline Technology Firm C Breakeven Year (1000 Runs)

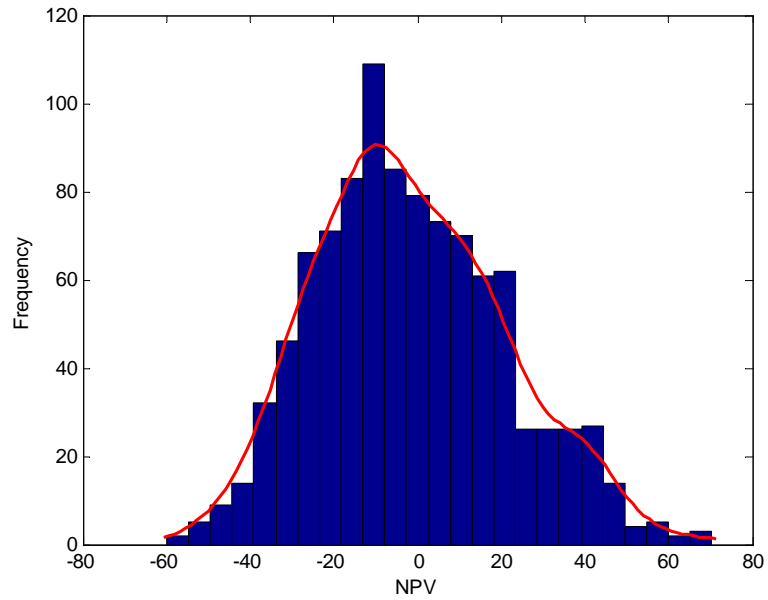


Figure 58: Distribution of NPV for the Baseline Technology Firm C (1000 Runs)

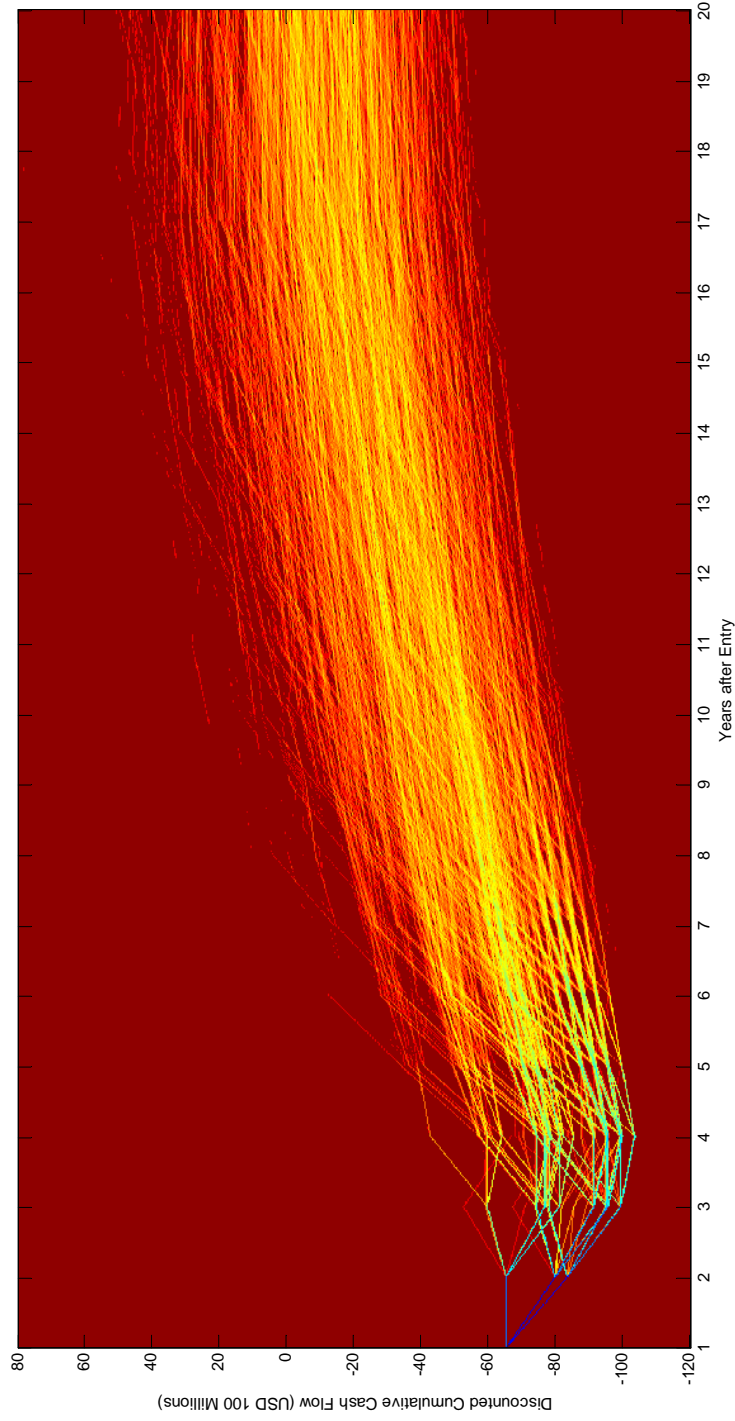


Figure 59: Discounted Cumulative Cash Flow for the Firm C Baseline Scenario (1000 Runs)

of NPV for the baseline technology scenario for Firm C. Due to the usage of discount factors and critical nature of decisions made in the first few years under competition, NPV distribution forms “steps”. This is an interesting find as other Monte Carlo methods that doesn’t involve discrete actions during the program lifecycle would perhaps not result in such situations. A typical response would resemble a normal distribution in most cases. Figure 59 helps visualize this observation. The decisions as well as the market outcome in the first few years open series of likely cash flow situations. However as the program continues, the distribution gets smoother.

### ***6.3 Readdressing the Primary Research Question and Hypothesis***

In summary, the following organic curiosity and investigation process were followed:

1. Commercial aircraft markets are dominated by aircraft families sharing common parts
2. Firms compete by introducing new derivatives resulting in a multi-firm, multi-product oligopoly
3. Demand is volatile, firms actively readjust strategies
4. From a designer’s perspective, how can we quantify value when it depends on the decisions of the program managers after the design is fixed?

Formally the research question was identified as:

**Research Question 1:** *For a given oligopolistic market system with inherent uncertainty, how can an aircraft manufacturer evaluate the expected family program value? How can we use this valuation technique to assess program risk of a new design?*

The literature review showed a series of new techniques within the domains of microeconomics that formally deal with the interaction of multi-product, multi-firm markets, and their entry/exit decisions. A cross-fertilization between engineering design and economics was thought to benefit the financial evaluation of aircraft projects. The status quo of such studies has been the technique of Net Present Value. Some of its disadvantages were identified and at the expense of computational complexity, the methodology created was a generic product family design methodology for market systems. Figure 33 shows the methodology.

**Hypothesis:** *Considering the dynamic, stochastic, competitive, and flexible nature of aircraft family programs, combining an Ericson Pakes class Industrial Organization model of dynamic oligopoly with Monte Carlo Simulations enables the designer to make risk-informed, value-driven platform design decisions in the conceptual design phase.*

It was shown that the methodology developed to test the hypothesis resulted in similar program values. However, due to multi-stage, competitive nature of such methods, now it is possible to have an extra information about a possible order of introduction for different derivatives. Even though the market risk is still a key driver in the outcome of these simulations, now it is possible to explicitly show the program risk instead of a single point of valuation for the program.

In the example case study, an experiment was conducted to test the hypothesis via comparative assessment. It is demonstrated that the standard Net Present Value methods, the benchmark, would lead to different decisions compared to the outcomes of the methodology presented in this thesis. It is also shown that the existing methods fail to quantify the risk which is defined as the probability of the program not breaking even. For certain technology scenarios, it is also demonstrated that the benchmark method could result in opposite signs of perceived returns for the program possibly influencing the top-level decisions. This was particularly highlighted for T2 Composite Wing Technology where the signs of program value estimation from two different methods were opposite. Without adequate risk quantification, this would result in a “go” situation for E[NPV] method and “no-go” for NPV method. Even with the positive sign that is obtained from the computationally more expensive but more comprehensive methodology introduced in this thesis, the high percentage of risk would deter cautious investors from investing in T2.

## CHAPTER VII

### CONCLUSION

#### *7.1 Contributions*

Designing for value is a popular concept. However, every program has its unique characteristics with different implications on the value metric. In this thesis, the characteristics of aircraft family design programs both on the technical and marketing sides were identified. It was seen that due to the multi-stage, multi-product, uncertain, and competitive nature of the aircraft market, standard valuation techniques such as NPV is not adequate to use as a single value metric. Instead a stochastic, dynamic, discrete game of incomplete information was solved to observe a distribution of outcomes. The problem was considered from a designers' perspective. In order to measure the added value and risk associated with a certain technical change, certain rules of the game were assumed as well as the mechanics of how the program managers would act in a dynamic market. The results were presented and compared to the traditional NPV technique.

The valuation methods for aircraft programs with after-design implications typically utilize real-options. The inability of real options techniques to directly deal with the competitive nature of such markets was shown from the literature review. Even though those techniques are proven and commonly used in many financial valuation studies, this methodology took a different path due to fore-mentioned specifics.

The problem was extended to a product portfolio management problem to show how firms may act different in dynamic, uncertain situations compared to static, deterministic situations. The example scenario included only three design points for the firm to enter which were quite desirable in means of ROI, however it was still possible to demonstrate that, due to the stochastic nature of the game rules, firms may hesitate, delay, or go for different strategies with certain probabilities.

The multi-firm, multi-product competition and market uncertainty that characterizes

the narrow-body market were investigated. Unlike the wide-body market, narrow-body market is easier to enter for smaller firms but the competition is stronger with very similar products. As the similarity of the products increases, due to strong competition, firms meet the demands of customers via product families which share common parts. This helps reduce the development costs as well as manufacturing costs and allow reduced time to market as the product platforms act as a “springboard” for development of similar products. Industrial Organization models such as Ericson-Pakes models combine inherent elements of the commercial aircraft market in a structured fashion to support analytical and rational decision making.

As a part of the solution to the subgame competition, a spatial utility model was applied. Though spatial models have originated to explain the consumer choices over geographic locations, the same analogy was used to define a spatial choice environment over the payload-range diagram for design missions of different candidate vehicles. This type of an approach is not very common in the field of econometrics as well as design-for-market-systems.

Three sub-questions accompanied the primary research question and answering those relied mainly on the literature review and the observations from the industry. This document could also serve as a rapid review source for researchers that would like to work on this topic.

Economists often deal with the steady-state distributions of the market structure whereas the interest in this thesis has been mainly on the evolution of the market year by year. This way, it is now possible to help identify the likely, value-adding steps in the development of a product family. Even though the steady-state probabilistic distribution of the market structure which occurs after a “sufficiently” long time can provide useful insights, it doesn’t present the necessary information to a researcher who is interested in certain aspects of a program such as the breakeven year and the discounted cash flow.

## ***7.2 Future Research Directions***

Using interdisciplinary methodologies in aircraft design offers promising benefits for identifying key strategies to maximize market success. However, such models often underestimate

the complex nature of the reality. More complicated models, specifically a family-specific cost model or a detailed narrow-body demand model would help increase the confidence level of those counterfactual experiments. For future reference, this framework can act as the cohesive environment if such models are available. Calibrating such models usually require firm-specific proprietary data which is unavailable to the public. In fact, accurately pinpointing the exact marginal production cost of a single aircraft is difficult to measure even for the manufacturer itself. On the other hand, it is very straightforward to assume the companies will have a full knowledge of the transaction value every time a new aircraft is sold. What is perhaps not completely certain to a manufacturer is the pricing of the competitors as well as the transactions in the used aircraft market.

Industrial Organization models are complicated models that are naturally capable of modeling imperfect competition. However, “curse of dimensionality” remains as a significant obstacle to using such techniques for more extensive applications. For this specific case, the real limitation was not in means of the number of firms in the market but in means of the number of design points, market structures, and dynamic cost elements. In a grand fashion, combined with detailed data, it would be an advanced and fully realistic study to apply to the entire LCA market and investigate the interactions on a bigger scale. Such an analysis would require large amounts of cost, transaction, and performance data as well as much exhaustive computations. Recent developments in the field of Industrial Organization and better-tailored algorithms as well as rapidly increasing computational power at researchers’ disposal can be the key to enabling such simulations. Advancements in the field of Industrial Organization will not only benefit the design for commercial aviation markets, but also the entire field of design for market systems.

In Section 6.1, five scenarios that can be simulated on this framework were identified but only one scenario was picked. Curious researchers will find it interesting to investigate specifically the Scenario 4 in which the regulations/goals and perhaps government subsidies impact the competition. In a game-theoretical sense, it may make sense for the players in an oligopoly setting not to invest in newer technologies as long as no one makes a move first. Provided that the outside good doesn’t contest strongly, value-maximizer firms may



choose to stay at a current technology level. This could hold true especially for the wide-body market where there are only two players and there is not a similar alternate for transoceanic flights.

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