An Approach to Analyze Tradeoffs for Aerospace System Design and Operation

by

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ABSTRACT

There are important tradeoffs that need to be considered for the design and operation of aerospace systems. In addition to tradeoffs, there may also be multiple stakeholders of interest to the system and each may have different preferences as to the balance amongst the tradeoffs under consideration. A tradeoff hyperspace is created when there are three or more tradeoff dimensions and this increases the challenge associated with resolving the hyperspace in order to determine the best design and operation of a system. The corresponding objectives of this research are to develop a framework to analyze tradeoff hyperspaces and to account for the preferences of multiple stakeholders in this framework.

The framework developed in this research is called the Tradeoff Analysis Framework and its applicability was evaluated through analyzing three different case studies in the aerospace domain, each progressively more complex in terms of applying the framework and exploring the impact of certain types or change, or innovation in the system of interest. The first case study analyzed the impact of changing aircraft cruise operations and one facet of the case study explored the impact of imposing a hypothetical tax on aircraft-produced contrails. From this study it was determined that airlines will change their behavior (*i.e.,* their perceived value-optimal cruise trajectory) in response to a tax placed on producing contrails where, the higher the tax, the less contrails they choose to produce. The second case study explored the impact of changes in aircraft approach procedures into Boston-Logan airport. In this study, there were multiple stakeholders, each with different preferences as to the balance amongst the performance and environmental tradeoffs considered. A key result from this study was that competing stakeholder preferences could be partially resolved, which led to the design new approach procedures that were beneficial to all stakeholders. The third and last case study examined the tradeoffs associated with using fractionated spacecraft for remote sensing space missions. Here, the current paradigm is monolithic spacecraft and it was found that despite fractionated spacecraft demonstrating more value-robustness than a comparable monolith, they fail to stay value-competitive to monoliths in terms of absolute value delivered. In particular, this occurs because presently the enabling technologies required for fractionated spacecraft are not yet mature and reliable enough at the performance levels needed for them to become viable alternatives to monoliths.

Along with insights gained in the case studies about the systems of interest, through applying the Tradeoff Analysis Framework insights were gained with respect to implementing the framework. These insights form the methodological contributions of this research since they offer opportunities to learn about the breadth of potential framework applicability and areas for subsequent improvements in the framework for future use.

BIOGRAPHICAL NOTE

Greg O'Neill grew up in Lewisburg, Pennsylvania and early on demonstrated an interest in mechanics, mathematics, and science. This interest remained with him through high school and following his graduation he chose to pursue engineering at the collegiate level. He began his engineering studies at Syracuse University in the Department of Mechanical and Aerospace Engineering in 2003. In May 2007, he graduated from Syracuse University with a Bachelors of Science in Aerospace Engineering and a minor in Mathematics and Economics. Then, in September 2007, he began his graduate studies at Massachusetts Institute of Technology, eventually completing his Master's of Science degree in February 2010. Upon completion of his Master's degree, he immediately began working on his Doctor of Philosophy degree. At MIT, Greg has maintained a socio-technical interdisciplinary education and research focus, primarily drawing from the fields of Aerospace Engineering, Systems Engineering (Theory), Space Systems, Aircraft/Air Transportation Systems, Mathematics, and Economics. He is particularly interested in designing and evaluating innovative systems (architectures) using a combination of technical system models, valuation theory, and economics.

Following the completion of his collegiate education, Greg plans to teach in a field related to Aerospace Engineering.

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In direct support of my research, I would like to acknowledge **Jean-Marie Dumont** for his contributions to the first case study used in my research. I would also like to thank **Neil Chen** and **Banavar Sridhar** at NASA's Aviation Systems Division who in part supported this research.

I would also like to acknowledge my **family and friends** who have supported me along the way and ultimately helped me mature as a person and as an educator. My experiences at MIT have reinforced their crucial role in my pursuit of excellence and I hope that the completion of my PhD may, in part, serve as recognition of their support in this continual pursuit.

Table of Contents

9

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AC	Aircraft
ADS_GNS	Attitude Determination System and Guidance Navigation System
ATC	Air Traffic Control
BOS	Boston-Logan International Airport
Comm_CS_C&DH	Communication, Command & Data Handling, and Computer System
ConOps	Concept of Operations
CFIT	Controlled Flight Into Terrain
CBA	Cost-Benefit Analysis
CER	Cost Estimating Relationship
cdf	Cumulative Density Function
DARPA	Defense Advanced Research Projects Agency
DNL	Day-Night Average Noise Level, A-weighted scale
dB(A)	Decibels on the A-weighted scale
DSN	Deep Space Network
DoD	Department of Defense
DoE	Design of Experiment
D	Destination (airport)
FAA	Federal Aviation Administration
FL	Flight Level
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System (Procedure)
INM	Integrated Noise Model – FAA Software
JFK	John. F. Kennedy International Airport
LAX	Los Angeles International Airport
MCA	Monte Carlo Analysis
NPIM	Noise and Performance Impact Model
O	Origin (airport)
ppm	Pixels per Meter
PCA	Principal Component Analysis
pdf	Probability Density Function
RNAV	Required Area Navigation
RNP	Required Navigation Performance
RWY	Runway
SET	Spacecraft Evaluation Tool
SLCC	Stochastic Lifecycle Cost
System F6	(DARPA) System Future, Fast, Flexible, Fractionated, Free-Flying (Program)
TRL	Technology Readiness Level
ToS	Time-of-Service
TWAP	Time-Weighted Average Performance
VM	Valuation Method
VARG	Value-At-Risk and Gain (curve)

NOMENCLATURE

<u>ALPHABET SYMBOLS</u>

c	=	innovation timeline constant, years (yrs)
CO_2	=	Carbon Dioxide, kilograms (kg) or metric tons (mt)
C_{Ops}	=	cost of flight path, United States Dollars
d_{track}	=	ground track distance, nautical miles (nm)
FT	=	flight time, hours (hrs)
FB	=	fuel burn, gallons (gals) or pounds (lbs)
NO_x	=	mono-Nitrogen Oxides NO and NO_2, kilograms (kg) or metric tons (mt)
$Pop_{DNL \geq 65dB}$	=	DNL population noise exposure, number of people exposed (ppl)
$Pop_{TA\,60dB}$	=	Time-above 60 dB population noise exposure, number of people exposed (ppl)
$\vec{P}_j$	=	preference structure for the jth stakeholder, varies
r	=	discount (inflation) rate, dimensionless
R	=	resolution, pixels per meter (ppm)
s	=	performance gain from innovation, varies
S	=	innovation profile, performance gain with respect to time
t	=	time, years (yrs)
$Thru$	=	aircraft throughput, aircraft per hour (AC/hr) or total aircraft (AC) per day
T_w	=	time window, years (yrs)
u	=	single attribute utility, dimensionless
$\hat{U}$	=	multiple attribute utility, dimensionless
$\vec{U}$	=	external factors, varies
$\vec{V}_j$	=	value proposition for the jth stakeholder, varies
$\vec{V}_j^*$	=	optimal value proposition for the jth stakeholder, varies
Y_i	=	i^{th} system output, varies
$\vec{Y}$	=	set of system outputs, varies
$\vec{Y}^*$	=	optimal system outputs, varies

21

$\vec{X}$ =   set of proposed system changes, varies

<u>GREEK SYMBOLS</u>

$\vec{\lambda}$ =   set of preference weightings, varies

λ_i = i^{th} preference weighting, varies

Λ_j =   value structure "importance" weighting for the jth stakeholder, dimensionless

1. RESEARCH MOTIVATION AND OBJECTIVES

There are important tradeoffs that need to be considered for the design and operation of aerospace systems. Tradeoffs specifically arise when a improving a given system objective requires the compromise of at least one other objective, and a tradeoff hyperspace is created when three or more tradeoff dimensions (*i.e.,* competing objectives*)* exist for a system. A notional tradeoff hyperspace is shown in Figure 1-1, which depicts multiple tradeoff dimensions for a generic system where each objective becomes a potential tradeoff with the other objectives for the system. A specific example of a tradeoff hyperspace is shown in Figure 1-2, which corresponds to the operation of an aircraft where environmental objectives such as emissions and contrails are considered along with "traditional" objectives such as performance, safety, and cost.
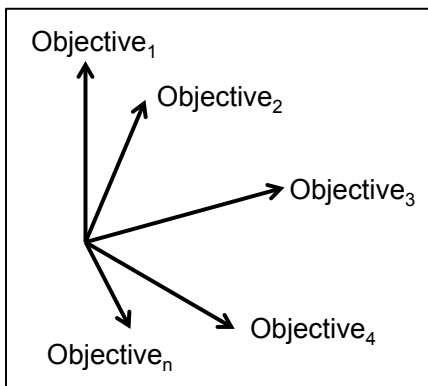
Figure 1-1. A Notional Tradeoff Hyperspace.
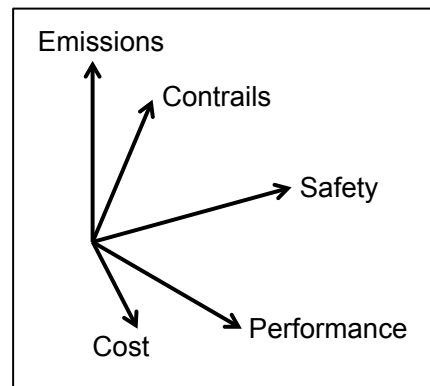
Figure 1-2. A Tradeoff Hyperspace for an Aircraft.

In addition to a tradeoff hyperspace, there may also be multiple stakeholders of interest to a system that will each have preferences as to the balance amongst the tradeoffs in the hyperspace. Exacerbating the difficulty of resolving a tradeoff hyperspace consequently arises if stakeholders have different preferences as to the balance amongst the tradeoffs under consideration. A simple example of this is shown in Figure 1-3, which shows the tradeoff between two arbitrary objectives where the two stakeholders of interest have different preferred balances of these tradeoffs along the line of feasible first and second objective values. Therefore, in

Figure 1-3. Competing Stakeholder Preferences in a Tradeoff Space.

summary, understanding and analyzing tradeoff hyperspaces is complicated and thus an approach is needed to achieve this that also accounts for stakeholders and their preferences. This observation leads to the two objectives of this research as summarized hereafter.

1. Develop a framework to analyze tradeoff hyperspaces

The first objective of this research is to identify key components for analyzing and articulating tradeoff hyperspaces and to organize these components into a coherent, usable framework. The framework development will be structured such that it is generalizable and can therefore be used to analyze tradeoff hyperspaces corresponding to the design and/or operation of many systems of interest. The resulting framework from this research used to analyze tradeoff hyperspaces is called the Tradeoff Analysis Framework.

2. Account for the preferences from multiple stakeholders

The second objective of this research is to account for the preferences of multiple stakeholders. These preferences are ultimately intended to provide a mechanism to structure and quantify the respective desirability of the stakeholders as to the balance amongst the system tradeoffs of interest. In the context of the tradeoff hyperspace in Figure 1-3, these preferences effectively become a means for stakeholders to negotiate with each other as to best balance amongst the system objectives, where each stakeholder may have unique preferences as to this balance.

In order to evaluate the applicability of the Tradeoff Analysis Framework, it will be used to analyze several relevant tradeoff problems in the aerospace field. This exercise serves as validation of the Tradeoff Analysis Framework and provides the necessary insights to reflect on the framework development and overall utility. The particular applications of the framework are purposefully scoped to assess tradeoff hyperspaces associated with changes in aerospace system design and/or operation, thereby providing a common source of motivation amongst the applications. Here, changes in system design and operation are considered to be any departures from the current, or existing design and operation of a system and thus may be interpreted as innovation in a system, depending on the context. The case studies sequentially grow in complexity in terms of the applying the framework as well as the type and magnitude changes, or innovation analyzed with the framework.

2. LITERATURE REVIEW – TRADEOFF ANALYSIS FRAMEWORKS

There is a class of frameworks offered in the literature that might be used to analyze the tradeoff hyperspaces associated with engineering systems. This class of frameworks is referred to as the multi-stakeholder, tradeoff analysis framework class. In order to provide context as to when frameworks belonging to this class may be of use, the first part of this section is used to position them within the systems engineering process. This discussion is then followed by a further discussion this framework class with specific examples.

2.1. Context – Systems Engineering Frameworks

Systems engineering frameworks are useful for positioning where the multi-stakeholder, tradeoff analysis class of frameworks may be of use in the engineering design and execution process. Systems engineering frameworks implicitly adopt a lifecycle, or beginning-to-end perspective of a system. Subsequently, these frameworks tend to be holistic and focus more on the key activities involved in developing, manufacturing, testing, deploying, and operating a system than on specific methods for executing these steps of the systems engineering process. One of the more common lifecycle or systems engineering frameworks is the V-Model framework and this is used to provide context as to where the multi-stakeholder, tradeoff analysis frameworks discussed in Section 2.2 may be of use.

2.1.1. The V-Model

The "V-model" framework entails key activities to be performed in developing and operating a system or, alternatively, executing an engineering program. A representative V-model is shown in Figure 2-1 (adapted from Ref. [1]). The two components of the V-model
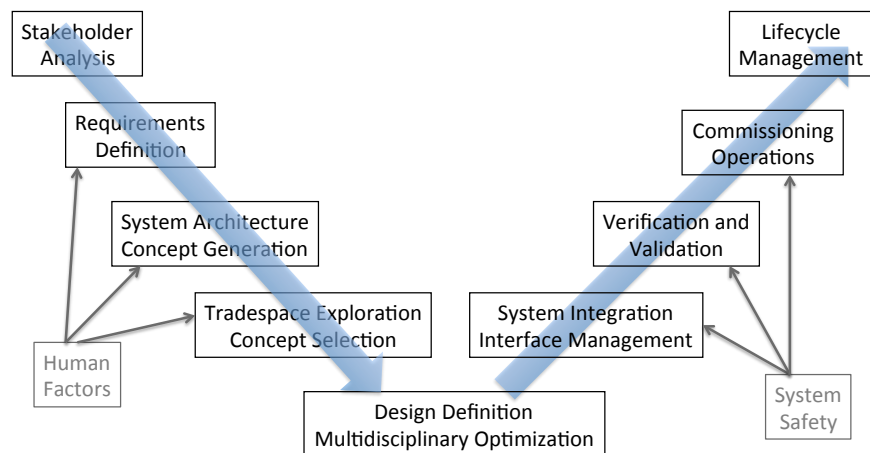
Figure 2-1. A V-Model Systems Engineering Framework.

are the system, or program definition (the downward arrow in Figure 2-1) and then the system integration, testing, and operation (the upward arrow in Figure 2-1). The key activities in the system definition include a stakeholder analysis and then, given a set of requirements, exploring the space of potential designs and

25

evaluating which designs are the most valuable. The outcome of the system definition process is a system to be manufactured, integrated, tested, and then operated. These activities collectively form the upward part of the V-model, which ends with the lifecycle management of the system.

In the V-Model process, the key activities associated with the system definition process are where the multi-stakeholder, tradeoff analysis frameworks discussed in Section 2.2 may be of most use, although this does not preclude their usefulness elsewhere in the V-Model. In particular, it is during these activities when the relevant stakeholders for the system of interest are identified and their needs are captured, which are then used to derive the requirements, or important objectives for the system. Since there are often multiple objectives, there may be tradeoffs amongst these objectives, thus requiring the use of multi-stakeholder, tradeoff analysis frameworks to explore potential concepts given these criteria. The multi-stakeholder aspect of these frameworks ultimately become of use when there are several stakeholders of interest, each with different preferences as to balance of these tradeoffs.

2.2. Multi-Stakeholder, Tradeoff Analysis Frameworks

Multi-stakeholder, tradeoff analysis frameworks can be used to analyze systems based on multiple criteria, or tradeoffs dimensions. In addition, these frameworks address competing stakeholder preferences as to the balance of tradeoffs under consideration, in at least some capacity. The common goal of multi-stakeholder, tradeoff analysis frameworks is therefore develop mechanisms for effectively resolving multiple criteria to rank a given set of system concepts (alternatives) in order to select the best, or most desirable option in the context of stakeholder preferences, or value. These frameworks are often developed such that they either specific to particular system and/or methods for analyzing tradeoff hyperspaces, or are generalizable to any methods and analysis. Several examples of multi-stakeholder, tradeoff analysis frameworks are provided hereafter.

2.2.1. Decision-based Design Framework

The decision-based design (DBD) framework was developed by Hazelrigg and it evaluates engineering products, that is, tangible systems or objects that have a corresponding market and ensuing demand and supply such that revenue is generated from the product given a sell price, P [2]. The DBD framework therefore implicitly considers the tradeoffs associated with engineering products along with including the relevant needs of the product developers, manufacturers, and customer market. The DBD framework was specifically founded upon the rationale that the design with the highest expected value is the preferred

26

design. The major characteristic of the DBD framework is that candidate alternatives, or products are ranked using expected utility and therein optimized to determine the highest value alternative, or candidate product [3,4]. An overview of the DBF framework is provided in Figure 2-2 (adapted from Ref. [2]).
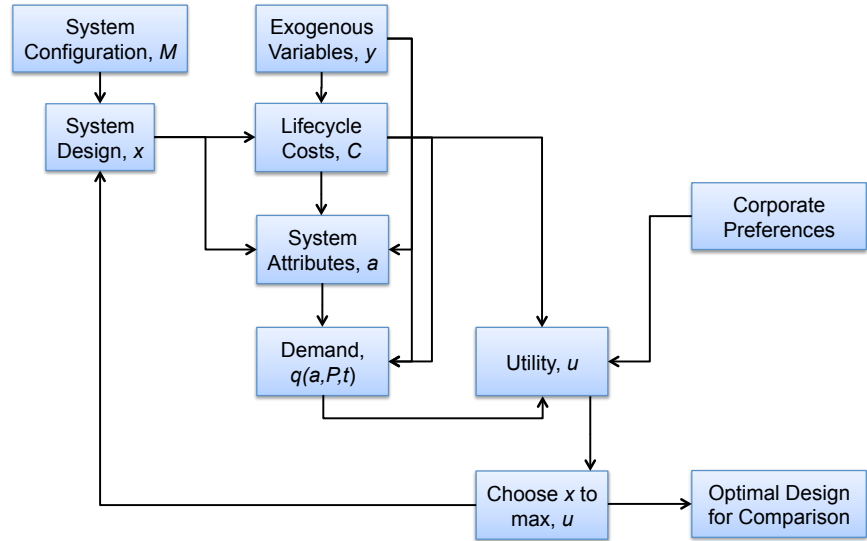
Figure 2-2. Decision-based Design Framework.

As seen in Figure 2-2, the inputs to the framework are the system configuration (*e.g.,* a product) along with the exogenous variables, which influence the system and, within the DBD framework, are prescribed as random variables characterized by either discrete or continuous probability distributions. In addition to these inputs, corporate, or stakeholder preferences are also input to the framework and these ultimately account for the needs of the customers for the system, or product of interest as well as that of the product developers and manufacturers. Given these inputs, the core of the framework is executed, which leads to the determination of the lifecycle costs of the system, the attributes of the system, and the demand for the system. The attributes of the system may characterize the multiple tradeoff dimensions of interest for the system and the demand for the system is ultimately dependent on the attributes, the price of the system, and time[1]. Given the lifecycle costs, corporate preferences, and demand, the utility of the system is then computed, therein forming the key input to the value-optimizer in the framework. The optimizer specifically chooses the system design, or configuration that maximizes the expected utility. The output of this, or more generally the DBD framework is the value-optimal design for future comparison.

2.2.2. Multi-Attribute Tradespace Exploration Framework

The Multi-attribute Tradespace Exploration (MATE) framework was developed by Diller and Ross and can be used to explore a number of designs, or configurations and then to evaluate those designs in a utility-cost

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[1] In the DBD framework, the price for the system is chosen to maximize the expected utility of the system, given the corporate preferences.

space [5,6]. Here, utility aggregates the attributes, or tradeoff dimensions of interest for a given design that are beneficial to the relevant stakeholders and positions them relative to the cost(s) of the design, therein positioning the value of the design as benefit versus cost. Analogous to the DBD framework, the implicit rationale adopted in MATE is that the designs with the higher expected value are preferred over those designs with the lesser expected value. While the core MATE process is discussed hereafter, the original MATE process was intended for use with integrated concurrent engineering (ICE) to facilitate the design and ensuing decision-making process in team-based working environments with multiple tradeoff dimensions and stakeholders of interest. It is also relevant to note that MATE was first developed in 2002 and since then a number of adaptations of the MATE process have been developed and applied and these include: MATE for Changeability (Dynamic MATE) [7]; MATE for Systems-of-Systems [8,9]; MATE for Flexibility [10,11]; and MATE for Survivability [12]. A corresponding overview of the core of the MATE process and thereby any subsequent version of MATE is provided in Figure 2-3 (adapted from Ref. [6]).

As seen in Figure 2-3, the core of the MATE process is iterative and it involves several key activities. The first activity is the stakeholder need identification process where the specific desires or preferences of the relevant stakeholders are determined and ultimately used to evaluate the candidate designs. The second activity is the architecture solution
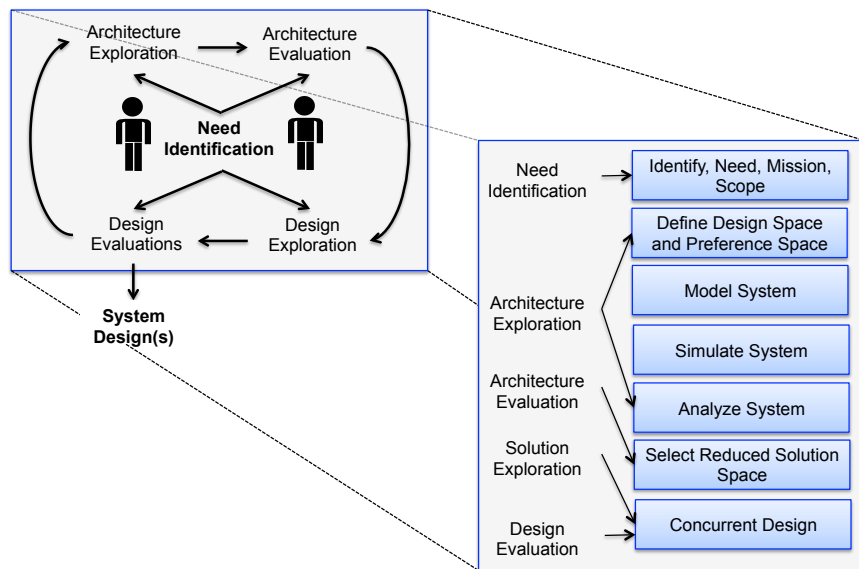
Figure 2-3. Multi-Attribute Tradespace Exploration Framework.

exploration. This activity involves defining the candidate designs to be analyzed, often by characterizing each design through a vector of variables and then modeling each candidate design vector. In order to ultimately evaluate and compare designs, the model must assign the corresponding attribute values to each design vector so that it can be mapped to a utility-cost space, where the attributes of interest are identified through the needs of the stakeholders. After this is complete, the utility-cost space consisting of several, or

28

many, candidate designs can be explored and evaluated by the relevant stakeholders, leading to the selection of the most stakeholder-desirable system design(s).

2.2.3. Change Propagation Analysis Frameworks

Change propagation analysis (CPA) frameworks include methods for tracking changes in often-complex systems with the goal of ultimately evaluating the impact of a potential change in a system [13–15]. Here, the impact may implicitly contain multiple attributes, or system objective tradeoffs based on stakeholder input just as is the case with the DBD and MATE frameworks. The commonality of change propagation frameworks is their reliance on Design Structure Matrices (DSM's) in order to characterize the interdependencies of a system's components and/or information flows (refer to Ref. [16] for a description of DSM's). Through characterizing a system in a DSM, changes in the system can be identified, tracked, and quantified, forming the basis for deriving measures of the type and magnitude of change in a system. For example, Griffin *et al.* assume the change in the density of a DSM is a proxy for the magnitude of change in a system and correspondingly offer the Change Propagation Index (CPI) metric for determining the level of change in a system, which is shown in Equation 1.

Equation 1

$$CPI_i = \Delta E_{out,i} - \Delta E_{in,i}$$

In Equation 1, CPI compares the binary entries in a DSM, which are characterized by the variable E, and determines whether or not the ith element in a DSM has changed because of any other element in the DSM. The CPI metric is then specifically the difference in change in the ith element from in the feed-forward (E_{in}) and feedback (E_{out}) portions of the DSM. In addition to deriving metrics such as CPI, the DSM characterization also enables CPA methods to be extended, for example, to evaluate the corresponding risk introduced in a system from change.

While there are several unique versions of CPA frameworks, the Change Prediction Method (CPM) from Clarkson *et al.* shown in Figure 2-4 is discussed as a representative example of such frameworks (image source: Ref. [13]). Clarkson's CPM framework can be parsed into three components: method inputs, method execution, and method outputs. The required inputs to this method are the product, or system of to be analyzed as well as any new product requirements, which lead to required changes in the product. Given these inputs, the CPM core execution activities include the initial analysis, where a model of the product and its respective subsystems is created, characterizing a product by a DSM, and computing predictive matrices, which lead to the creation of a product risk matrix. The second core activity in the

29

CPM is the case analysis where new product requirements lead to required changes in the system, which are then combined with the product risk matrix to formulate the case risk plot. This plot ultimately depicts each subsystem in terms of the likelihood and impact of change in a subsystem on the overall risk of the system.
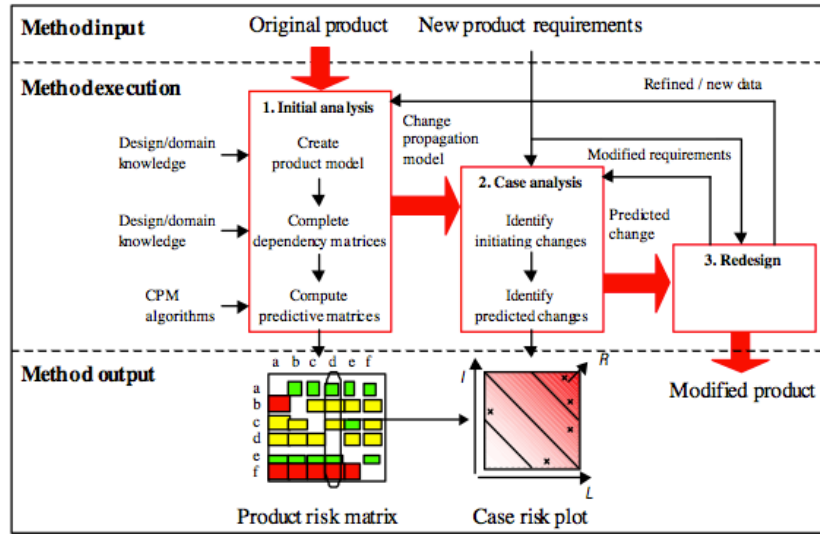
Figure 2-4. Change Prediction Method Framework.

Recall that this impact may consist of multiple system objectives based on stakeholder input to the CPM process. The information provided from the case risk plot can then be used to redesign the system to mitigate the identified sources of risk in a system.

2.2.4. Hazard and Risk Analysis Frameworks

Hazards lead to potential risk in engineering systems and thus an important aspect of evaluating engineering systems is to analyze these potential sources of risk, if they are to be safe and successful in operation. Hazard and risk analysis frameworks specifically address this through evaluating how design decisions affect the reliability or risk imposed by a system, where there may be different sources of risk such as that arising from the reliability of system hardware or potential operator error. Benefits from applying hazard and risk analysis frameworks and methods may include, for example, exposing single point failure modes in a subsystem assumed to be redundant and therein identifying opportunities for mitigating risk through functional redundancy. Most hazard and risk analysis frameworks are meant to analyze a system in order to mitigate residual risks in that system before it is fielded and two common hazard and risk analysis frameworks are Failure Modes, Effect, and Critical Analysis (FMECA) [17] and Systems-Theoretic Accident Modeling and Process (STAMP) Hazard Analysis [18]. The hazard and risk framework discussed hereafter is suggested as an improvement upon the STAMP hazard analysis and was developed by Marais [19]. This framework is shown in Figure 2-5 (image source: Ref. [19]).

Marais's hazard and risk analysis framework focuses on identifying the impact of organizational factors on risk and provides several benefits including the early identification of risk, determining the most valuable allocation of resources to mitigate risk, and provides an ability to continuously monitor risk. And within Marais's framework, stakeholder input and the existence tradeoffs in the risk
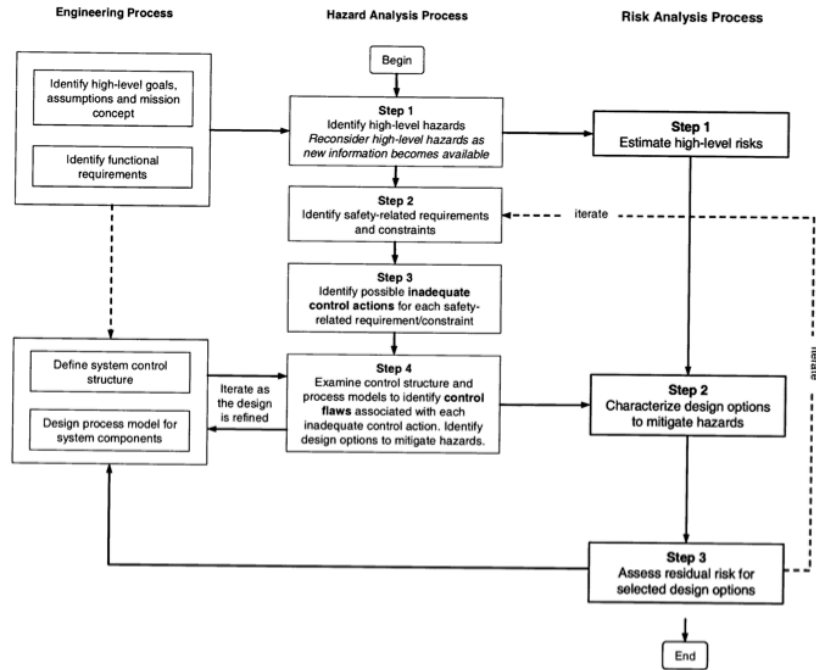
Figure 2-5. A Hazard and Risk Analysis Framework.

domain are important considerations. The first two components of Marais's framework, the engineering process and hazard analysis process, are the STAMP hazard analysis method. Within this method, the engineering process is specifically responsible for developing the underpinning of the system of interest such that it can be analyzed in order to identify potential sources of risk. The hazard analysis then involves executing four steps: (1) identify high-level hazards; (2) identify safety-related requirements and constraints; (3) identify possible inadequate control actions for each safety requirement; and (4) identify control flaws. Marais's framework extends these two aspects of the STAMP hazard analysis with a third component: risk analysis. The risk analysis is specifically responsible for estimating the high-level risks given the identified hazards in a system, developing design options or adaptations to mitigate these hazards, and then assessing the residual risk for the design options considered. From the output of the risk analysis, the design option that best mitigates potential risk in the system of interest can be determined.

2.2.5. Multi-Actor, Multi-Criteria Analysis Frameworks

Multi-actor, multi-criteria analysis (MAMCA) frameworks are another type of framework that can be used to analyze the tradeoff hyperspaces associated with the design and operation of a system while considering the needs and preferences of multiple stakeholders. MAMCA frameworks tend to be the broadest and most generally applicable for analyzing systems since they are often not overly specific to a particular system, or

31

method of interest. MAMCA frameworks specifically consider the preferences of multiple stakeholders in order to develop a set of criteria to evaluate candidate system designs or configurations. One example of a MAMCA framework is that developed by Macharis *et al.*, which is shown in Figure 2-6 and used as a representative example of such frameworks [20].
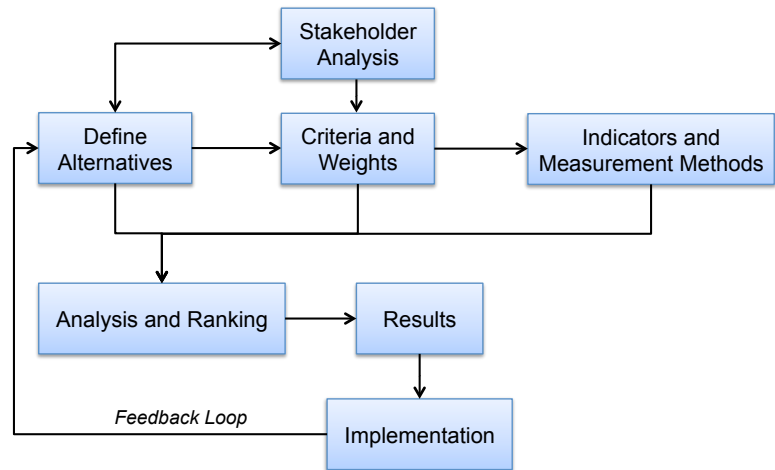
Figure 2-6. Multi-Actor, Multi-Criteria Analysis Framework.

Macharis's MAMCA framework begins with a stakeholder analysis. This analysis is used to identify the relevant stakeholders given the system of interest and then to use their needs as the criteria basis for evaluating a set of system design alternatives. Depending on the formulation of criteria used, this may include weighting the criteria in a relativistic sense in order to establish a ranked ordering of the most to least important criterion. Following this, the criteria from multiple stakeholders is used to develop indicators and measurement methods that use the (weighted) criteria from the various stakeholders to ultimately evaluate alternative system designs or configurations. This step of the process may implicitly involve selecting the best set of stakeholder criteria for inclusion in the analysis. Following the analysis of the systems, they can be ranked in terms of the stakeholder-derived criteria. Once this is complete, the results, in terms of the preferred system design for each stakeholder, can be compared. The remaining step in the method is then implementation, which is the process of using the framework iteratively in order to refine stakeholder preferences with the goal of having the stakeholders reach some consensus about the best system design or configuration.

2.2.6. Negotiations

Given a tradeoff hyperspace for a system, negotiations can be useful for facilitating consensus amongst stakeholders if there are competing preferences as to the balance of tradeoffs amongst the stakeholders. There are many, formal negotiation approaches to facilitate alignment and this is discussed in additional detail in Section 4.3.4. However, to provide an example of such an approach, Game Theory is briefly explored hereafter. Game theory is a theoretical framework for characterizing and predicting the outcome of games created by a group of players, when *rationality* is assumed, that is, more value offered by a system

is more desirable to stakeholders. Game Theory was originally developed John von Neumann and greatly complemented by John Nash [4,21–23]. One extension of Game Theory developed by Nash led to Nash Bargaining, which is a theory based on the non-cooperative theory of games and bargaining models. This theory may subsequently be of use to resolve competing stakeholder preferences as to best balance of tradeoffs in a given hyperspace. The bargaining model relies on a preference and payoff structure for each stakeholder (*e.g.,* some value function such as expected utility), which truncates the various tradeoff dimensions of interest to a single metric, or value. The ensuing suggested optimum, or Nash Bargaining Solution is the most efficient point in the tradespace for maximizing the aggregate value of the stakeholders, which happens to be the tangent to any location on the Pareto Front of value corresponding to acceptable set of agreeable solutions amongst the stakeholders of interest. A simple two-dimensional example of this is conceptually depicted in Figure 2-7 where the Nash Bargaining solution is on the Pareto front of value between two arbitrary stakeholders, Stakeholders A and B, given their respective valuation of the tradeoff dimensions of interest. Any point on the Pareto Frontier would suffice, hence the negotiation aspect of this Game Theoretic approach for facilitating multi-stakeholder negotiations.
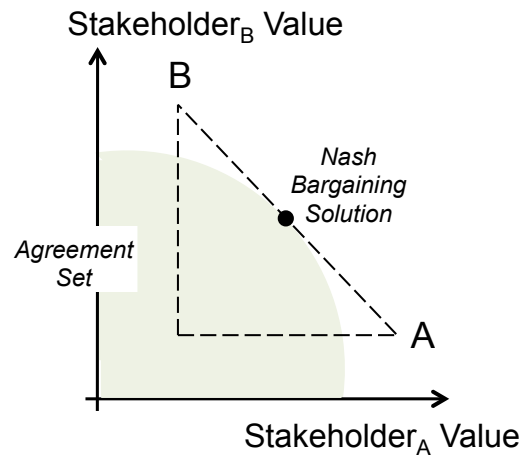
Figure 2-7. Nash Bargaining.

2.3. Observations from the Literature

The frameworks for evaluating engineering systems cited in the literature all have the common goal of determining the best, or most valuable system design or configuration given a set of criteria derived from stakeholder needs and preferences. In the context of the motivation of this research, the criteria evaluated with these frameworks might be implied to include the relevant tradeoffs (or tradeoff hyperspaces) for the system of interest. In reflecting on the types of frameworks examined in the literature, the systems engineering frameworks are the most holistic in terms of the beginning to end process of designing, developing, and operating a system. Subsequently, the multi-stakeholder, tradeoff analysis class of frameworks mentioned in the literature may be applicable at various stages of the process prescribed by systems engineering frameworks. In terms of general applicability, the multi-stakeholder, tradeoff analysis frameworks that are tailored to a given set of methods or investigation focus of interest, which includes the

33

DBD, MATE, CPA, and Hazard and Risk Analysis Frameworks in Sections 2.2.1 - 2.2.4, will likely have a more limited scope of applicability than the MAMCA framework. For a specific example of this consider the DBD framework (Section 2.2.1), which optimizes a system based on expected utility. Therefore the users of the framework are to conform to this methodological prescription for evaluating engineering systems, which may not be less appropriate than some other, better evaluation approach or method. Thus, while these tailored frameworks are of great value for their intended applications, one potential limitation of these frameworks is the breadth of their applicability as result of the overly specific methods or approaches prescribed by these frameworks. The MAMCA framework discussed in Section 2.2.5 does not inherently contain this limitation since this approach is purposefully general to any system of interest and the ensuing methods and criteria used to evaluate the system.

3. LITERATURE REVIEW – INNOVATION ASSESSMENT FRAMEWORKS

The applicability of the Tradeoff Analysis Framework developed in this research to analyze tradeoff hyperspaces in the context of stakeholder value is evaluated through several case studies (see Sections 6-8). In these case studies, the framework is specifically used to evaluate the impact, or tradeoffs associated with change, or innovation in aerospace systems, depending on the case study context. Therefore, given this scoped application of the Tradeoff Analysis Framework, it is relevant to mention some related approaches in the aerospace literature offered for evaluating the impact of changes, specifically innovation in aerospace system design and operation, which is the subject of this section.

3.1. Overview

There have been numerous, formal approaches offered in the aerospace literature for analyzing the tradeoffs associated with aerospace systems. Of particular interest to evaluating the applicability of the Tradeoff Analysis Framework developed in this research are those works that develop formal approaches for assessing how *changes* in the design and/or operation of a system impact its potential value delivery to the relevant stakeholders. Here, changes in system design and operation are considered to be any departures from the current, or existing design and operation of a system and thus may be interpreted as innovation in a system, depending on the context. The resulting relevant literature therefore draws from four different fields: Decision Analysis, Technology Forecasting and Management, Space Systems, and Aircraft Systems (see Figure 3-1). The space and aircraft systems fields are important because these form the basis for the specific systems eventually analyzed to evaluate the applicability of the framework in the case studies; the relevant literature belonging to these domains is presented in the case studies considered in this research (see

Sections 6-8). The decision analysis literature is presented in Section 4.3.2- 4.3.4 and it deals with research on methods for resolving tradeoff hyperspaces, as they are defined in Section 1, and resolving competing preferences amongst multiple stakeholders. And the technology forecasting and management literature is used to identify and structure the
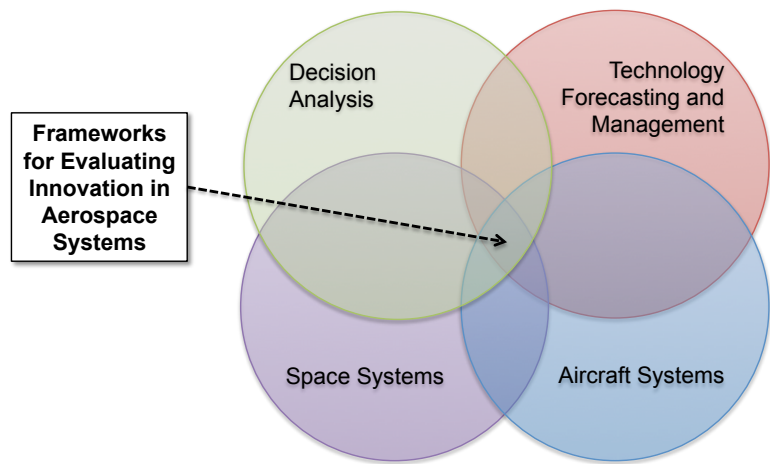
Figure 3-1. Literature Overview.

35

type and magnitude of proposed changes to the design and/or operation of a system before it is analyzed with a given framework or approach; this literature is discussed in Section 4.2. As shown in Figure 3-1, the confluence of these four literature fields is the development and application of frameworks to analyze tradeoff hyperspaces associated with change, or innovation in aerospace system design and operation, while considering multiple stakeholders of interest. The scope of the following literature review is therefore research that contributes to this confluence of research fields, namely, "Frameworks for Evaluating Innovation in Aerospace Systems."

3.2. Literature

Several sources from the aerospace domain are used as examples of the formal approaches or methods contributed to the confluence of research fields shown in Figure 3-1. The commonality of these works is their emphasis, in varying capacities, on evaluating the tradeoffs associated with innovation in aerospace system design and operation, depending on the context. This literature scoping was specifically chosen since the applicability of the framework developed in this research will be evaluated by analyzing the tradeoffs associated with change, or innovation in systems. The relevant, formal approaches in the literature are briefly discussed hereafter.

1. **Technology Metric Assessment and Tracking (TMAT) Process** [24]. The TMAT process is used to evaluate the tradeoffs associated with inserting new technologies in systems and the five major steps of the TMAT process include:

    1. Technology metric (*i.e.,* measure of success) identification

    2. Technology audit scheme definition and information gathering, which collects data regarding the expected impact of new technology and probability of achieving that impact

    3. Technology metrics assessment, which maps the information obtained in Step 2 to quantifiable metric forms

    Figure 3-2. TMAT Process for Tracking Technology Impacts.

    4. Technology metrics integration, which quantifies the impact of technology via the metrics

    5. Technology metrics sensitivity analysis, which quantifies the change in impact due to any modeling assumptions.

36

The TMAT process is notionally a linear, feed-forward approach and the result of applying TMAT process is a model of technology impacts over time as shown in Figure 3-2 (Image source: Ref. [24]). In Figure 3-2, the x- and y- axes are time and technology improvement, respectively. Despites its linearity, the innovation profile in Figure 3-2 has probability distributions along it that define confidence regions in technology improvement over time.

2. **Cardinal Technology Readiness Scale Valuation** [25]. This approach to analyzing systems simply maps the impact of innovation in system design and/or operation to a continuous Technology Readiness Level (TRL) scale, thereby providing technology readiness levels for all integer and non-integer TRL values between 1 and 9. The resulting continuous TRL scale can be used to identify the risk and readiness of new technologies to a more granular degree, which may be of value when the changes to a system are similarly granular.

3. **Internet–Accessible Technology Risk Assessment Collaborative System (ITRACS) and Framework for Advanced Systems Tradeoffs using Probabilistic Analysis of Concepts and Technologies (FASTPACT)** [26]. The FASTPACT approach is used to quantify the impact of new technology (or technology portfolios) on a program's figures of merit based on information from applying ITRACS, which solicits expert opinions on the probability of technology performance success. This approach can therefore account for multiple stakeholders and their respective value through the figures of merit. This method was applied to NASA's Next Generation Launch Technology project in Ref. [26].

4. **Technology Performance Risk Index (TPRI)** [27]. TPRI tracks technology readiness throughout a lifecycle and is comparable to the TRL scale and can thus be used to analyze the impact of innovation in a system's design and/or operation. TPRI specifically achieves this by determining how well a technology is meeting its performance requirements and, if not, this determines a performance risk in a system due to the technology. This approach was applied to a generic weapon system in Ref. [27].

5. **Developmental Maturity Index (DMI)** [28]. The DMI is suggested as being an improvement to the TRL scale for capturing technology maturity and therein the impact of changes, or innovation in a system's design and/or operation. The DMI is quantified through a two-step process with an emphasis on maintaining continuity throughout the process. The two steps used to quantify the DMI for a given system are:

   1. Technology maturity evaluation
   2. Evaluation of the reduction in risk imposed by new technology

6. **Failure Modes, Effect, and Critical Analysis (FMECA)** [17]. FMECA is a structured approach that provides valuable insights as to how design decisions affect reliability, for example, the downstream impacts of innovation on a system's respective reliability. Benefits of applying FMECA may include: exposing single point failure modes in a subsystem assumed to be redundant; identifying opportunities for functional redundancy; and permitting components to assume a safe mode in the absence of required signals or power. There are numerous versions of the FMECA approach but they all have the common objective of identifying sources of risk in a system as the result of changes in that system. For example, in Ref. [17] FMECA was applied to the Space Test Program, specifically to minimize the risk of inserting new technology in military or civil space missions.

7. **k-σ Technology Risk Model**

   In addition to the previously mentioned approaches that can be used to assess the impact of innovation in systems, there is a body of work with the common objective of assessing reliability improvements in initially immature technologies over time, either holding technology performance constant, or allowing it to vary. These studies specifically build their respective approaches using probabilistic technology readiness (*e.g.,* TRL) distributions for subsystems and payload technologies to capture the impact of increases in technology maturity, and potentially performance, over time. Given their focus, the changing parameter is often the reliability (or probability) at which the desired performance is achieved with a given technology [29–36]. Many of these works use the k-σ Technology Risk Model to generate distributions of technology performance gains and losses as a function of the technology's TRL; a good example of one of these distributions can be found in Ref. [30] and is shown in Figure 3-3. These distributions assume that performance probabilistically

38

degrades with TRL and are subsequently generated from Weibull distributions dependent on a "k" Factor, which is a variable reflecting the potential performance loss and gain of a technology determined from expert interviews. An example of one of these distributions is shown in Figure 3-3 (Image source: Ref. [30]). Figure 3-3 shows probability density functions corresponding to some arbitrary k-factor
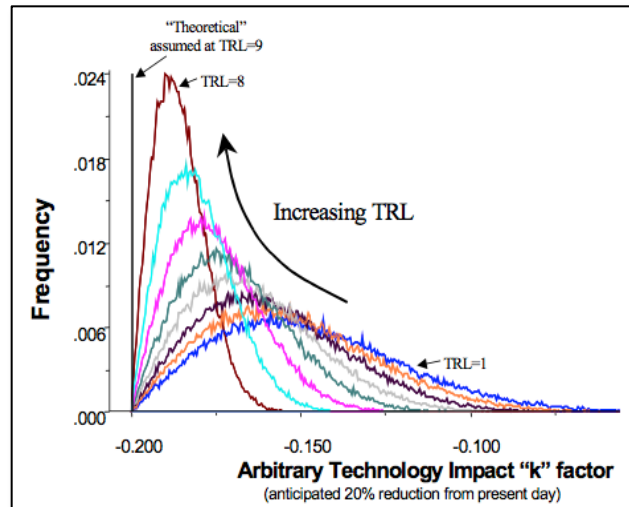
Figure 3-3. K-σ Technology Readiness

(in this case lower k-factor values are more desirable). Each TRL has a dedicated density function and, intuitively, as TRL increases, the probability of realizing a lower k-factor also increases; this establishes the increasing compression and leftward shift of the TRL distributions seen in Figure 3-3.

Certain works using the k-σ Technology Risk Model select the optimal technology (or technology portfolio) to pursue using a heuristic optimizer to balance performance gains with technology risk due to increasing innovation [30–33], and one of these works does so while also allowing the type of technologies available to change over time [35]. For those works using the K-σ Technology Risk Model that assume technology performance is constant, an implicit assumption is therefore that the desired level of technology performance is always available and that the innovation of that technology is only manifested through continuously reducing the risk of that technology (in time).

3.3. Tradeoff Analysis Framework Motivation

The previously discussed literature provides a variety of approaches and methods for analyzing aerospace systems, with an emphasis on evaluating the impact of innovation in system design and operation. One observation from this literature is that with the exception of the FASTPACT approach, the approaches offered all focus on one metric, or objective to capture the result of a proposed change to the system of interest, thereby ignoring the existence of potential and relevant tradeoff hyperspaces for the system. Furthermore, the approaches do not explicitly consider and thereby provide formal provisions for accounting for the relevant stakeholders of interest to the system under consideration, which may be

important to the overall evaluation of the system. Lastly, the approaches offered adopt a singular emphasis on evaluating the impact of performance and reliability improvements in technology *or* operational changes to a system and, in many cases, the approaches are tailored to the system of interest. The major drawback from this latter observation is an immediate constraint on the breadth of applicability of the approaches offered in the literature if they are overly specific to a system. These observations from the relevant literature do not negate the utility of the frameworks offered therein, but motivate the need for a broadened framework to analyze the tradeoff hyperspaces associated with changes, or innovation in system design and operation that adopts a system-agnostic and macroscopic view of the tradeoff assessment problem.

4. TRADEOFF ANALYSIS FRAMEWORK

In order to address the first objective of the research, the Tradeoff Analysis Framework was developed, which is capable of analyzing the tradeoff hyperspaces associated with the design and operation of systems. Three versions of the Tradeoff Analysis Framework will first be discussed, the: Baseline Framework, Framework with Multiple Stakeholders, and the Framework with Optimization. The majority of this section is then devoted to discussing specific elements of the framework in more detail along with potential opportunities to further mature the framework development and thereby increase its utility.

4.1. Tradeoff Analysis Framework Overview

This section presents the three versions of the Tradeoff Analysis Framework.

4.1.1. Baseline Framework

The first version of the Tradeoff Analysis Framework is the Baseline Framework, which is shown in Figure 4-1. As seen in the figure, in the Baseline Framework, the analyst is the user of the framework, and at the core of the framework is the *system*, which is often a representation of the system of interest (*e.g.,* a model). The system
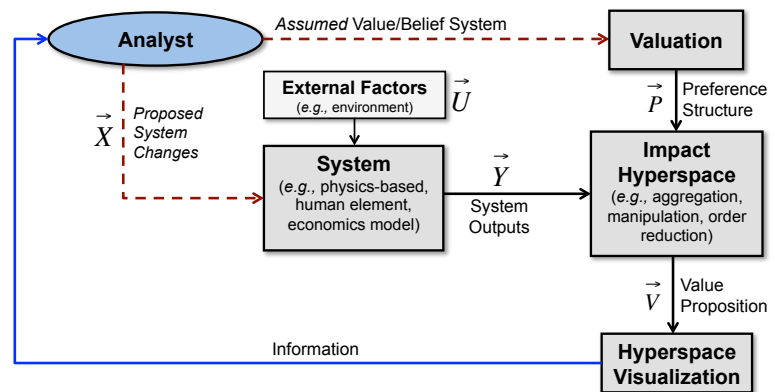
Figure 4-1. Baseline Framework.

operates in a specific context, which is characterized by the *external factors*, *U*. The *system outputs, Y*, are the tradeoff dimensions of interest and when influenced by a *proposed change* to the system, *X*, they characterize the impact of the system. These tradeoff dimensions ultimately constitute the tradeoff hyperspace to be analyzed with the framework. The system outputs are inputs to the *impact hyperspace* where they may be combined with the preference structure to form the value proposition, which is then conveyed to the *analyst*. The analyst has a value or belief system indicative of their perceived importance of the system outputs, which may change based on new information provided from the hyperspace visualization. The *valuation* aspect of the framework formalizes these belief systems into preference structures, *P*, which, as previously stated can be combined with the system outputs in the impact hyperspace to generate value propositions, *V*. These value propositions are then conveyed back to the analyst via the hyperspace

41

visualization, thereby closing the framework cycle. Since the analyst is the user of the framework, they may propose changes to the system in accordance to their own, or an assumed belief system.

4.1.2. Framework with Multiple Stakeholders

The second version of the Tradeoff Analysis Framework is the Framework with Multiple Stakeholders. This framework version is shown in Figure 4-2 and this framework version extends the Baseline Framework to include any relevant stakeholders to the system of interest. The new consideration in the Framework with Multiple Stakeholders is therefore the
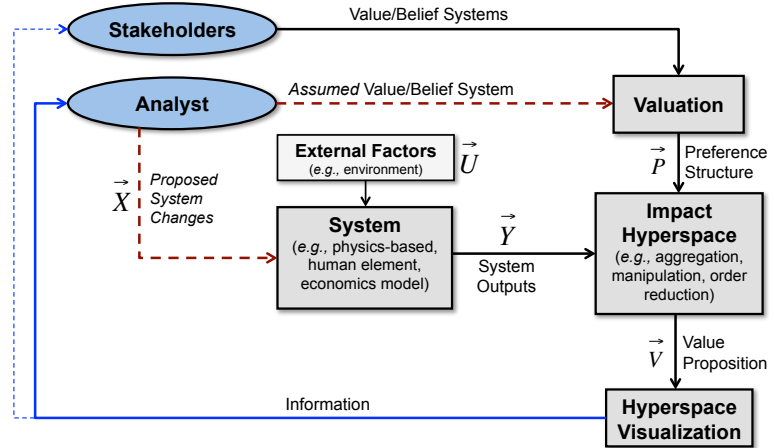
Figure 4-2. Framework with Multiple Stakeholders.

respective value/belief systems of the stakeholders, which are addressed through the valuation component of the framework as previously discussed for the analyst in the preceding section. One additional change in the Framework with Multiple Stakeholders is that the value propositions are fed back to the analyst as well as the stakeholders, keeping in mind that the analyst is still the only one who can propose changes to the system. It is important to note, however, that the framework does not preclude a stakeholder from being the analyst.

4.1.3. Framework with Optimization

The third version of the Tradeoff Analysis Framework is the Framework with Optimization. This framework version is shown in Figure 4-3. In order to use this version of the framework, the valuation aspect of the framework must be used to define a value function for each stakeholder; valuation is discussed in detail in Section 4.3.2. In the Framework with
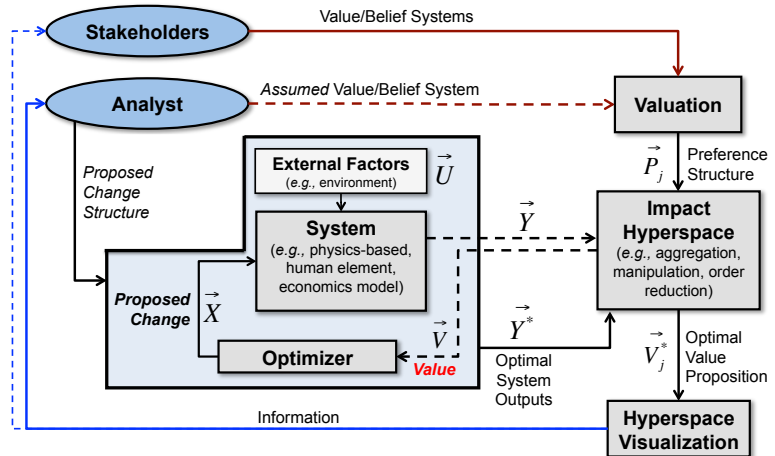
Figure 4-3. Framework with Optimization.

42

Optimization, an optimizer is used to determine the most valuable proposed change (*e.g.,* design and operation of a system) given a value function. This value function may correspond to one stakeholder or may be a supra-stakeholder objective function as described in Section 4.3.4. The role of the analyst in the Framework with Optimization is different than in the other framework versions because they now provide the proposed change structure rather than the proposed change itself, which is needed for the optimization algorithm. As seen in the Framework with Optimization, there is an iterative inner loop consisting of the optimizer, which proposes a change to the system and then computes the system outputs given that change. Once this is complete, the feedback occurs, which involves sending the system outputs into the impact hyperspace and then combining them with the preference structure to yield the value of a given change. The value of this proposed change is then used by the optimizer to propose another perhaps more valuable change to the system. Several potential usages of the Framework with Optimization are briefly summarized hereafter.

1. **Quantifying the drivers for optimal value:** The Framework with Optimization might be used to quantify the drivers for optimal value. This is specifically achieved by quantifying the sensitivity of value relative to the system outputs, or proposed changes in the framework. This sensitivity may show that certain system outputs/proposed changes are more dominant than others in terms of value, and thus they will have a stronger influence in the decision-making process for determining the most valuable design/operation of a system.

2. **Determining the Pareto Front:** The Framework with Optimization might be used to determine the Pareto Front in a given system output space, which consists of proposed changes that are strictly non-dominated, that is, the most valuable proposed changes, given a specific preference structure. A non-dominated proposed change cannot be improved upon with respect to all of the system outputs by any other proposed change. Therefore, non-dominated proposed changes will correspond to a set of system outputs where at least one output is optimal in terms of desirability. The advantage of determining the Pareto Front is that it may be a (very) small subset of the entire proposed change space and it shows the key tradeoffs in the system output space, which may aid in the stakeholder decision-making process.

43

3. **Directed search:** The Framework with Optimization might be used to search the solution (system output) space. This provides a mechanism for exploring proposed changes in an educated, rather than random fashion by using the underlying optimization algorithm rules. For example, with a gradient-based algorithm, it may be possible to find value-sensitive paths/regions through the proposed change space, which may be more desirable to explore over value-insensitive paths/regions.

There are a few things to consider before using the Framework with Optimization. The first is that it requires a value function, which may not be possible to derive given the stakeholders of interest. Additionally, the Framework with Optimization may not guarantee that the optimum can be found depending on the optimization algorithm used. And lastly, selecting the best optimization algorithm to use in the Framework with Optimization is not trivial and depends on several key considerations, including the: problem (system model); linearity or lack thereof of the solution (system outputs) relative to the design variables (proposed system changes); resources available to implement and execute the optimizer; and fidelity of the system model or representation. Given these considerations, the major tradeoff in using the Framework with Optimization is that between the accuracy of the results (system outputs), given the system model, and the resources required to find the optimum.

4.2. Structuring the Proposed Changes

A constructive way to structure the proposed changes in the Tradeoff Analysis Framework is through the Change Taxonomy developed in this research. This taxonomy specifically structures the proposed changes through changes in a system's design and/or operation, which are two common types of change observed in engineering systems. One advantage of using the taxonomy is that different applications of the framework can be compared on the basis of the type and magnitude of proposed changes examined, which ultimately leads to a valuable discussion about the broader tradeoffs associated with changing a system's respective design and/or operation, as will be demonstrated through the three case studies (Sections 6-8) and summary discussion in this research (Section 9). This section begins by discussing the taxonomy and then subsequently uses it to position the sources of change observed in two historical engineering programs.

4.2.1. The Change Taxonomy

Progress in the aerospace field is invariably coupled with change and the Tradeoff Analysis Framework can be used to assess the tradeoffs associated with change in a system. For aerospace systems, change often manifests itself as innovation in a system through improvements in technology as well as improvements in the operation of the system. In order to structure the type
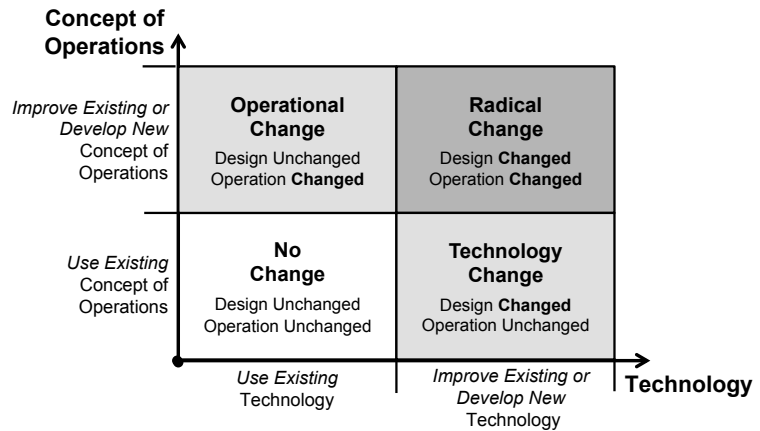
Figure 4-4. The Change Taxonomy.

and magnitude of changes in a system before begin analyzed with the framework, this research develops the Change Taxonomy shown in Figure 4-4 to categorize potential sources of change in engineering systems. In this taxonomy, change occurs along two dimensions: improvements in system technology or concept of operations (ConOps); these two dimensions are based on recommendations from the technology forecasting and innovation management literature [37–40]. Technology and ConOps specifically lead to changes in the design of a system (via changes in hardware/configuration) and the operation of a system (via changes in system usage), respectively. The two change dimensions in the taxonomy create four potential categories of system design and/or operational change; these are depicted in Figure 4-4 and adapted from Henderson and Clark [41]. The first category, *No Change*, uses the current or existing technology (design) and ConOps (operation) for a system; therefore, this category is often considered the datum, or baseline system state. The two mutually opposing categories of change are *Technology Change* and *Operational Change* where only the system design or operation is changed, respectively. Design changes specifically arise from improving existing technologies or developing and subsequently improving new system technologies, whereas operational changes arise from changing a system's respective ConOps. The remaining type of change in the taxonomy is *Radical Change*, which is a coupled combination of improving both system technology and ConOps. This coupled change may lead to the most significant change in a system from its present state, which correspondingly may lead to the most notable changes in the cost-benefit (impact) tradeoffs of a system given its present state. Consequently, given the magnitude of change associated with Radical Change, it may also introduce the highest risk.

4.2.2. Using the Change Taxonomy to Analyze Historical Engineering Programs

This section is devoted to demonstrating how changes, or innovation progressed in two historical programs in the aerospace literature via the Change Taxonomy developed in this research. These retroactive, conceptual applications demonstrate the structured approach the taxonomy provides for analyzing the impact of innovation, or more generally changes in a system given the Change Taxonomy discussed in Section 4.2.1. While these historical applications of the framework do not go into the depth that the formal case studies in the research do, they ultimately support one unique contribution of this research in examining the impact of simultaneous, coupled change in aerospace systems, albeit from a historical perspective (refer to Section 9).

The first case study (*i.e.,* framework application) is concerned with analyzing innovation in the Deep Space Network (DSN) during the period from 1960 to 1996. The DSN is a ground-based, communication network spread across the globe that can support space missions and also be used for making astronomical observations. Given its intended purpose, innovation in the DSN is assumed to be the data rate transmission capability of the DSN, since this dictates the level of service it can provide at any one time. The second case study concerns itself with aircraft safety, specifically, avoiding controlled flight into terrain (CFIT) incidents through innovation in aircraft technology. CFIT incidents are instances of aircraft colliding with the ground or water under full pilot control and these were the leading cause of aviation accidents and fatalities in the world at least through the late 1990's [42,43]. Reducing CFIT accidents was addressed through innovation in aircraft technology, which has greatly reduced the number of CFIT incidents observed in the present day [42]. In terms of the Change Taxonomy discussed in Section 4.2.1, the DSN and CFIT case studies collectively demonstrate change along both the ConOps and Technology axes.

4.2.3. The Deep Space Network

The Deep Space Network or DSN was designed to serve as a global communication network to support interplanetary space missions as well as to perform astronomical observations of the solar system and beyond. The history of the DSN is well summarized in Ref. [44,45] and the origins of the DSN program began around 1958. Before the DSN was officially sanctioned, the U.S. Army and Jet Propulsion Laboratory (JPL) developed the precursor to the DSN system and program. Eventually, in January 1961, the Deep Space Instrument Facility (DSIF), which was under NASA and JPL supervision, was created to manage the communication network originally created by the U.S. Army and JPL. Then between 1961 and 1963, the precursor to the DSN was managed and supervised by a myriad of offices and directorates. The

46

DSN program was eventually created in December 1963 to serve as the principal organization to support the DSN ground station network under supervision from NASA and JPL. In the DSN, operational innovation arose through an increase in the number of antennas in the DSN (to improve and increase coverage) as well as the complexity of DSN missions, as measured by the distance of missions from the Earth and the stages of the mission managed [44]. And technology innovation in the DSN program occurred through advances in antenna design as demonstrated in Figure 4-5 (Image Source: Ref. [44]).

DSN Antenna Composition Timeline (All Facilities Combined)

26-m Polar converted to 34-m STD Polar

64-m Az-el converted to 70-m Az-el

	1965	1970	1975	1980	1985	1990	1995	2000
11-m OVLBI Tilt/Az-el	0	0	0	0	0	0	0	3
34-m HBS Az-el	0	0	0	0	0	0	1	2
34-m BWG Az-el	0	0	0	0	0	1	2	6
70-m Az-el	0	0	0	0	0	3	3	3
34-m HEF Az-el	0	0	0	0	2	3	3	3
34-m STD Polar	0	0	0	3	3	3	3	0
64-m Az-el	0	1	3	3	3	0	0	0
26-m X/Y	0	2	3	3	3	3	3	3
26-m Polar	6	6	4	1	0	0	0	0
26-m Az-el	1	1	1	1	1	0	0	0
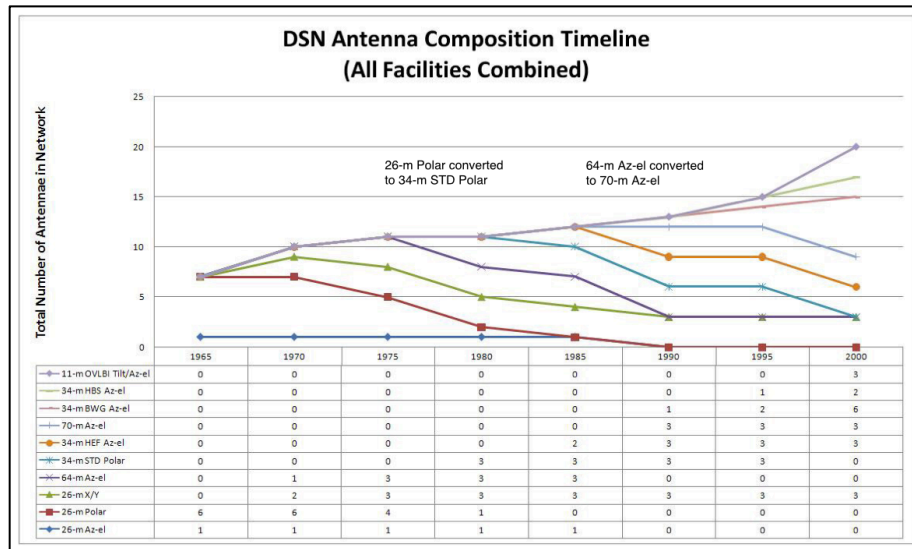
Figure 4-5. Technology Innovation in the DSN.

In Figure 4-5, the acronyms are as follows: Standard (STD), High-Speed Beam Waveguide (HSB), High-Efficiency (HEF), Beam Waveguide (BWG). These antennas are mounted with an Azimuth-Elevation (Az-el), Polar, X/Y, or Tilt/Az-el configuration. As seen in Figure 4-5, technology innovation in the DSN occurred through advances in antenna design efficiency (via increases in antenna diameter, antenna noise reductions, and increasing marginal power returns) and the subsequent updating of legacy antennas to improve their efficiency. This is substantiated in Figure 4-5 by the increasing number of efficient antennas in the network (*i.e.,* the BWG and HBS antennas). In addition, in recent years, interferometers have been created with the DSN, which significantly increases the performance of the DSN but requires the innovation of certain technologies, specifically, accurate ground station timing and positioning capabilities and special data processing [46–49].

The DSN ConOps innovation can be measured by the DSN's ability to manage a mission [44]. Here, innovation arises from the ability for the DSN to manage missions at an increasingly further distance away from Earth and also through managing missions with more complex stages (*e.g.,* manned missions, a probe

exploring a extraterrestrial surface). Innovation in DSN ConOps also arises from an increase in the number of antennas used in the DSN and changing the location of the antennas; the former trend is shown in Figure 4-5. A summary of the increase in complexity of DSN-supported missions can be found in Table 4-1 (Image Source: Ref. [44]). In Table 4-1, missions within a given decade are a uniform color and as time progresses, the red intensity of decades increases. As seen in the table, the red intensity increases towards the bottom of the table and towards the right, which represents innovation in ConOps through an increase in the distance of missions from the Earth and an increase in the difficulty of the mission stages managed by the DSN, respectively.

MISSION COMPLEXITY TABLE			Probe Flyby	Probe Orbit	Probe Impact	Probe Land	ProbeLiftoff	Probe Surface Explore	Probe Base	Probe Base w/ Samples	Manned Orbit	Manned Land, Explore, Liftoff	Manned Base
Location with Distance from Earth			P1A	P1B	P2	P3A	P3B	P3C	P4A	P4B	M1	M3	M4
Inner System	Earth	0 AU	x	1958							1962		
	Moon	~0 AU	1959	1966	1964	1966	1967				1968	1969	
	Sun	1 AU	x	1960									
	Venus	0.28 AU	1962	1990	1994								
	Mars	0.5 AU	1965	1971		1976		1997					
	Mercury	0.61 AU	1974	(2011)									
Asteroid Belt			1973										
Outer System	Jupiter	4.2 AU	1973	1995	1995								
	Saturn	8.5 AU	1979	2004		2005							
	Uranus	18.2 AU	1986										
	Neptune	29.1 AU	1989										
	Pluto	38.5 AU	(2015)										
Transient Small Body	Comet		1985										
	Asteroid		1991	2000		2001							
Interstellar			2003										

Table 4–1. ConOps Innovation in the DSN.

APPLICATION OF THE CHANGE TAXONOMY

The previously discussed forms of innovation in the DSN can be characterized through the Change Taxonomy developed in this research (see Section 4.2.1). Figure 4-6 shows the DSN innovation within the structured Change Taxonomy. Here, No Change is the current DSN with its present antenna efficiency, size, and
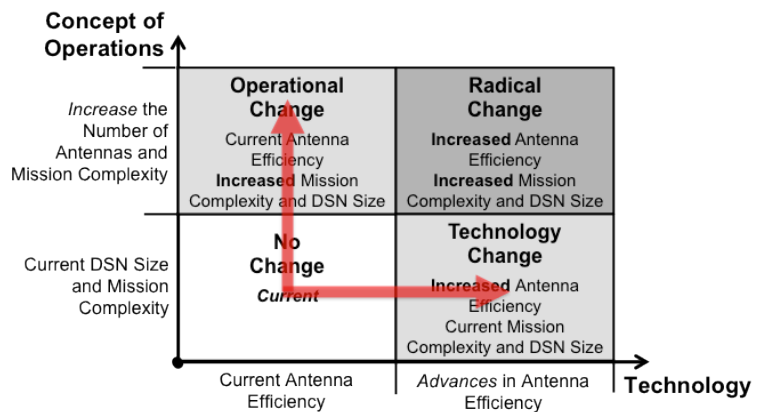
Figure 4-6. DSN Innovation (Change) Progression.

mission complexity.   Technology Change occurs through increasing antenna efficiency via increases in antenna diameter size, noise reductions, and in creasing marginal power. And Operational Change occurs through increases in the number of antennas in the DSN network (and implicitly changes in location), as

48

well as the management of more complex missions (refer to Table 4-1). Thus, the Change Taxonomy in this research captures the various sources of technology and ConOps innovation observed between any two periods in the DSN program. Furthermore, it is constructive to use this Change Taxonomy to understand the progression of innovation in the DSN program from its conception and initial usage in 1960. Based on the innovation trends shown in Figure 4-6 and Table 4-1, which parses the DSN progression into distinct periods, the DSN program always demonstrated punctuated periods of either technology *or* ConOps innovation (change), but never both at the same time. Thus, innovation in the DSN was never coupled, that is, technology and ConOps were never simultaneously demonstrated, thereby demonstrating an instance of Radical Change.
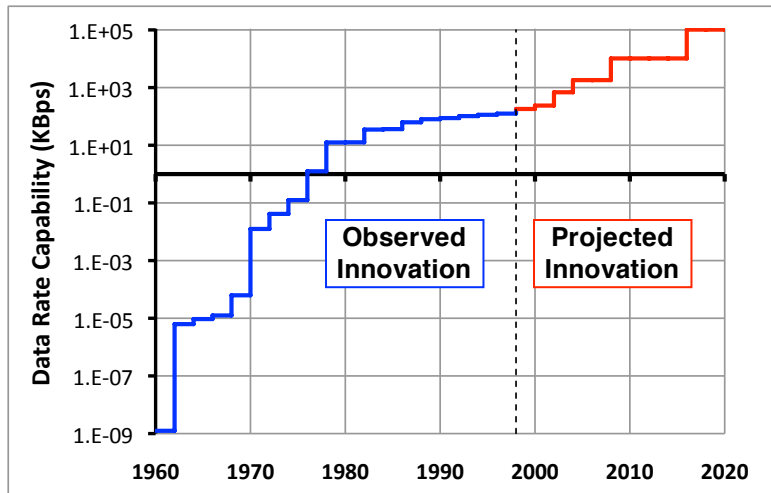
Figure 4–7. DSN Performance Gains due to Innovation.

The DSN performance resulting from innovation can be captured through gains in the data transmission capability since this dictates: (1) how many missions can be managed of a certain complexity and (2) the equivalent detection capability of objects in space a certain distance away from Earth. An adapted version of Mudgway's analysis of DSN performance gains from 1957-1998 is shown in Figure 4-7 [45]. This figure shows the increase in data rate capability due to innovation in the DSN until 1998; thereafter, the data rate capability increases are only projections into the future. As seen in Figure 4-7, performance gains vary widely between 1960 and 1998. In certain cases large gains are made every two years, whereas in other cases marginal gains are realized during a two-year period. The large gains are likely the result of technology innovation in the DSN, namely, through advances in antenna hardware or the addition of new antennas, whereas the small gains are more likely due to changes in DSN ConOps using the currently available antennas/hardware.

4.2.4. Controlled Flight Into Terrain

The second historical application of the Change Taxonomy is in analyzing progression with respect to avoiding controlled flight into terrain (CFIT) incidents, which occur when aircraft collide with the ground

or water while under full pilot control. Therefore, these incidents are often the result of crew error, instrument error, air traffic control error, or poor weather conditions [42,43,50]. CFIT incidents were the leading cause of aviation accidents and fatalities in the world at least through the late 1990's, and the decrease in CFIT incidents since then is one of the most significant changes and improvements in aviation safety in the last thirty years. In large part, this is due to the development of new technologies to improve aircraft situational awareness. The major source of innovation leading to the reduction of CFIT incidents was in the development and subsequent improvement of the ground proximity warning system (GPWS). Work on reducing the number of CFIT incidents began in the 1960's and by 1974 the FAA mandated that certain aircraft types must be equipped with terrain awareness warning systems (TAWS's), and by 1976, all airlines/aircraft were required to comply with the FAA-mandated TAWS's. (The motivation for the initial FAA-imposed mandate was an aircraft crash in 1974 at the Washington-Dulles airport where the aircraft collided with a mountain while following orders from ATC for final approach, killing all 92 passengers aboard [50].)

As mentioned previously, the major source of innovation that lead to the reduction of CFIT incidents was through developing and improving TAWS's. The objective of TAWS's is providing a pilot with both a visual and auditory warning of imminent collisions. The GPWS was developed in the 1960's and it was the first major TAWS. It specifically worked by measuring the distance between an aircraft and the ground via a radar altimeter, this being the key GPWS technological enabler. With the GPWS, imminent threats were determined by monitoring the rate at which an aircraft's distance above the ground is changing. The limitation of the GPWS was that it could not detect potential collisions with objects directly ahead of the aircraft such as a mountain. The use of GPWS's began in 1970 and by 1974 the number of successful collision detection warning cases improved from 33% to 90%. However, a study of fatalities by accident category between 1986 and 1995 conducted by the International Civil Aviation Organization (ICAO) and Volpe determined a need for further
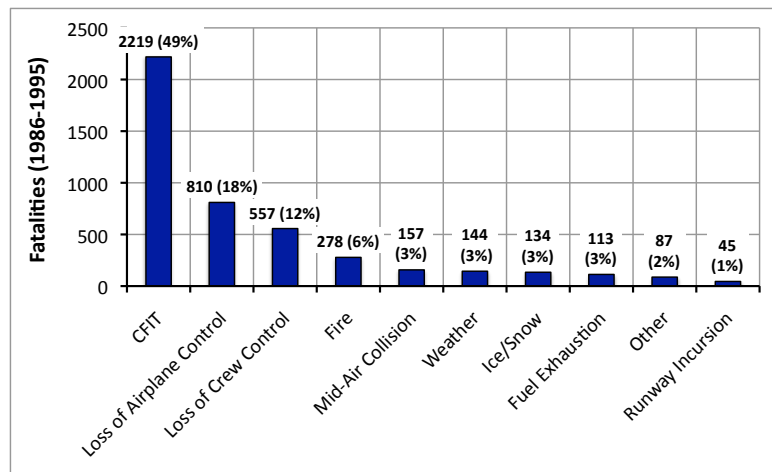
Figure 4-8. World Airline Fatalities (1986-1995).

50

reduction in CFIT incidents and thus a better early detection/warning system than the GPWS; the results from this study are summarized in Figure 4-8 (reproduced from Ref. [42]). As seen in Figure 4-8, despite the use of GPWS's and a nearly three-fold improvement in successful detections, from 1986-1995, nearly half of the world's aviation fatalities were the result of CFIT incidents. This prompted further improvements in GPWS's and the eventual development of the enhanced GPWS (EWGPS), which in addition to a downward radar altimeter has forward looking radar, thus allowing for detection of imminent CFIT threats in a lateral direction. While, the rate of CFIT incidents has significantly decreased today as compared to the number of incidents in 1995, these incidents still do occur and research and development continues to further improve aircraft situational awareness.

APPLICATION OF THE CHANGE TAXONOMY

The innovation, or change observed in the CFIT case study can be characterized through the Change Taxonomy developed in this research as shown in Figure 4-9. In the case of CFIT incidents, innovation has occurred along the technology axis, specifically through the development and improvement of TAWS's, thus no instances of Radical Change were observed as shown in Figure 4-9.

Figure 4–9. CFIT Innovation Progression.

While aircraft operations may have changed due to improvements in TAWS's, these were not the direct innovation focus in avoiding CFIT incidents, and therefore ConOps change is not observed in the case study.

The performance gains from innovation in TAWS's can be measured as a function of the number of airline fatalities per year attributed to CFIT incidents. Ref. [42] quantifies the history of CFIT incidents from 1945-1995 and subsequently demonstrates that improvements in TAWS's such as the GPWS and the EGPWS have appreciably reduced the number of fatalities attributed to CFIT incidents. However, as of 2003, CFIT incidents still accounted for 17% of all aviation fatalities, so motivation remains for continuing to improve TAWS's for aircraft to further reduce the number of aviation fatalities attributable to CFIT incidents [51].

51

4.2.5. Observations from the Historical Applications

The two previous retroactive applications of the Change Taxonomy to the DSN and CFIT (incidents) programs were intentionally simplified but still highlight a an attribute of the taxonomy. Namely, the Change Taxonomy developed in this research can capture the forms/types of change, or innovation found in these two case studies. Thus, this taxonomy is constructive for understanding how change evolves in real engineering programs and it may also be possible to use it at any point in a program to identify where investments in innovation are currently being allocated. Furthermore, using the taxonomy to plot the progression of innovation over the lifetime of a given program would provide a descriptive history of innovation in the program, which may prove very valuable

4.3. Extended Framework Discussion

This section is devoted to exploring the framework and its functionality in more detail. As such, several key aspects of the framework will be discussed along with potential opportunities to further mature the framework development and increase its potential utility.

4.3.1. System Transform

The system transform is the core of the framework and its respective purpose is to generate the system outputs, which are the tradeoff dimensions of interest, given a proposed change. The components of the system transform within the framework are highlighted in Figure 4-10. As shown in Figure 4-11 in additional detail, the system transform
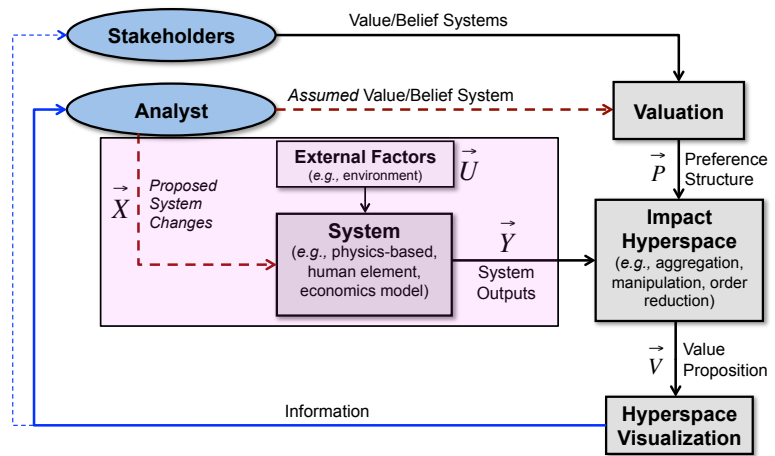
Figure 4-10. Framework: System Transform stem Transform.

is a transfer function that quantifies the system outputs, Y, given a proposed change, X, subject to the external factors, U. The system component within the transform is a representation of the system of interest and can therefore be a theoretical model or even based on data from an experiment, as long as it generates the system outputs of interest, given a proposed
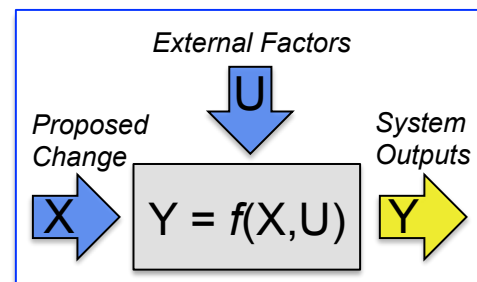
Figure 4-11. System Transform.

change and the external factors. Another comment regarding the system transform is that time is implicitly captured in the system and external factors. Therefore, the system outputs reflect the time period implicitly contained within the system and external factors.

4.3.2. Valuation

The valuation aspect of the framework quantifies a stakeholder's preference, or desire for a proposed change given the system output hyperspace dimensions; the valuation process is highlighted in Figure 4-12. Stakeholder valuation is specifically achieved by mapping the set of system outputs to value via a preference structure, P, as shown in Equation 2 where P is an operator on the system outputs, Y.
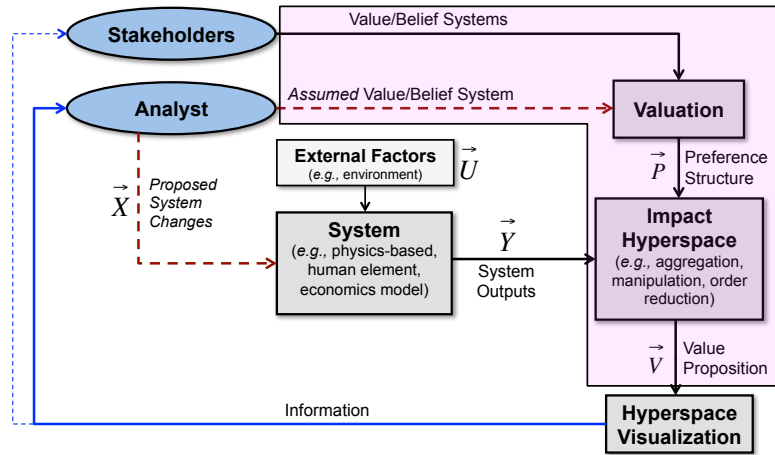
Figure 4-12. Framework: Valuation.

Equation 2

$$Value \equiv V = P\langle Y\rangle$$

One option for deriving the preference structure is to use valuation methods, all of which share the common goal of mapping system outputs to value via a formalized preference structure. There are numerous valuation methods that may be viable options for use in the valuation component in the framework. Selecting the best valuation method for a particular framework application depends on the underlying assumptions and capabilities of the valuation methods. Ross *et al.* discuss prominent valuation methods in order to provide guidance for practitioners in choosing the most appropriate method for a particular application [52]. While valuation methods are used in numerous applications, quantifying human preferences is a challenging task, so many of the valuation methods can lead to preference structures with considerable uncertainty and this should be appreciated when executing the framework. The last comment regarding valuation is the form of the preference structure as this may have implications for the framework execution and the ultimate representation of value. There are two common preference structure forms: uniform and variable, and there are two types of variable preference structures, linear and non-linear. Uniform preference structures are independent of the respective values of the system outputs of interest

whereas variable preference structures assign changeable preferences to the system outputs, which are dependent on the respective value of the outputs.

COST-BENEFIT ANALYSIS

One of the more common valuation methods is cost-benefit analysis (CBA), which is briefly described hereafter as an example of one potential valuation approach for use in the framework. CBA is a prescriptive valuation methodology that quantifies value through the net benefits yielded by a system relative to its respective net costs [53,54]. CBA therefore interprets value as benefit less cost mapped to a common measurement scale. Thus, CBA serves as a useful value-centric tool for cardinally weighting the positive and negative effects of various outcomes and combining them into the single metric of value. The preference structure for CBA consists of functions that map each system output to the measurement scale of interest, for example, a monetary scale. One common CBA function form is uniform-additive. This CBA function form specifically uses uniform multipliers to map each cost and benefit to a common measurement scale (*e.g.,* United States Dollars); these multipliers are tradeoff ratios, or relative preference weightings amongst the costs and benefits. The general form of an additive cost-benefit function with uniform preference weightings is given in Equation 3 (adapted from Ref. [55]).

Equation 3

$$Value = P\langle Y \rangle = \sum_{\forall t} \frac{\sum_{i=1}^{m}\left(\lambda_i \cdot Y_i(t)\right)}{(1+r)^t}$$

In Equation 3, *Value* is the benefit of a system less it respective cost. The discount rate, *r* is the rate of return on future investments, assumed constant; *[t_k, t_l]* is the time interval during which the system outputs are quantified; $Y_i(t)$ is the ith system output and λ_i is the ith uniform preference weighting corresponding to the ith system output, respectively. If λ_i is negative and positive, then the ith system output is a cost and benefit, respectively – thus, *Value* is benefit less cost. The set of *Y's* are the system outputs in Figure 4-12, and the set of λ's are collectively referred to as the "λ-Set" and are the embodiment of the value/belief systems in Figure 4-12. If the time scale associated with the cost and benefit quantifications is small (*e.g.,* several hours), discounting is negligible and Equation 3 simplifies to:

Equation 4

$$Value = P\langle Y \rangle = \sum_{i=1}^{m}\left(\lambda_i \cdot Y_i\right)$$

The sign of *Value* in Equation 3 and Equation 4 is indicative of the relative contribution of cost and benefit to value; if *Value* is positive, benefits contribute more to value than costs and the converse is true if *Value* is negative.

One advantage of a cost-benefit function is the ability to represent value on a cardinal measurement scale, which allows relative differences in value to be quantified, something not possible with ordinal value (preference) functions such as Expected Utility [3,4,52,56]. There are several benefits to having a cardinal value function, including the ability to create a value-ranked ordering of system options (*e.g.,* proposed changes), for a given λ-Set, and this may enable the design and operation of a system to be optimized as a function of value, as will be explored the first case study in this research (see Section 6).

Despite the aforementioned advantages, there are a few assumptions made by the cost-benefit function shown in Equation 3 and Equation 4 [3,57–59]. First, the costs and benefits must be normalized, via the λ-Set, to common scale (*e.g.,* United States Dollars), which may require liberal assumptions regarding the respective definition of λ for certain costs and benefits. Second, it assumes that the costs and benefits embody a system of "checks and balances" so there is no arbitration, that is, gaining an advantage in one cost/benefit cannot occur without sufficiently compromising on other costs/benefits. Third, for uniform-additive, cost-benefit functions, the preference weightings are constant, which is an assumption countered by a tendency of individuals to weight losses more than gains (see Prospect Theory [60–62]). And lastly, the definition of value is dependent on the λ-Set, therefore the valuation of an identical set of costs and benefits by two different λ-Sets cannot be compared and this may have adverse implications for stakeholder negotiations.

4.3.3. Identifying Stakeholder Misalignment

In accounting the value structures corresponding to multiple stakeholders with the Tradeoff Analysis Framework, it may be used to identify stakeholder misalignment relative to the system outputs. Stakeholder misalignment may occur if stakeholders have dissimilar preferences for a given system

$$
\begin{array}{c}
\begin{array}{ccc} \text{sh}_1 & \text{sh}_2 & \text{sh}_3 \end{array} \\
\begin{array}{c} \text{Output}_1 \\ \text{Output}_2 \\ \text{Output}_3 \\ \text{Output}_4 \end{array}
\begin{bmatrix}
\lambda_1^1 & \lambda_1^2 & \lambda_1^3 \\
\lambda_2^1 & \lambda_2^2 & \lambda_2^3 \\
\lambda_3^1 & \lambda_3^2 & \lambda_3^3 \\
\lambda_4^1 & \lambda_4^2 & \lambda_4^3
\end{bmatrix}
\end{array}
\longrightarrow
\begin{array}{c}
\text{Assumed λ-Set} \\
\begin{bmatrix}
1 & 0 & -3 \\
2 & 0 & 2 \\
6 & 1 & 5 \\
-4 & 0 & 2
\end{bmatrix}
\end{array}
$$

Figure 4-13. Identifying Stakeholder Misalignment.

output or set of outputs. The preference structure generated from the valuation process (see Section 4.3.2)

may be used to identify potential stakeholder misalignment. For example, consider the scenario depicted in Figure 4-13, which assumes the uniform-additive, cost-benefit function given in Equation 4 and a hypothetical scenario where there are four system outputs of interest and three stakeholders, each having different preference structures (the stakeholders are denoted as "sh" in Figure 4-13). The preference structure for each stakeholder is conceptually represented in the matrix on the left in Figure 4-13 and, using a uniform-additive cost-benefit function, the weighting factors or "λ-Set" values for each stakeholder are shown in the matrix on the right in Figure 4-13; note that these weighting values are arbitrary and map each of the four system outputs to a monetary scale where the negative and positive preferences values contribute to the costs and benefits of value, respectively.

Identifying stakeholder misalignment with the preference structure depends on two factors, first, the direction or sign of the preference structure. Using the cost-benefit function example in Figure 4-13, stakeholder misalignment may arise over the first output where stakeholders 1, 2, and 3 have λ's of 1, 0, and -3, respectively. Here, a positive and negative λ indicates that the perceived value of the output is a benefit and cost for stakeholders 1 and 3, respectively, whereas the value of the first output does not contribute to the second stakeholder's overall value since λ is 0. The second factor that stakeholder misalignment depends on is the sensitivity of the preference structure to value. For example, if the overall value of the outputs is highly sensitivity to the preference structure, then even preference structures with the same direction/sign (or of similar forms) may lead to different stakeholder perceived value, which is a source of misalignment. Conversely, if the preference structure is relatively insensitive to value, then potentially large differences in stakeholder preference structures with the same direction/sign (or form) will cause stakeholders to still be fairly well aligned in terms of overall value.

Identifying stakeholder misalignment is important because any misalignment is an opportunity for conflict, which will need to be resolved in order to decide on the best design and operation of a system. A common situation of conflict occurs when a subset of the stakeholders under consideration bear many of the costs but receive few of the benefits, or vice-versa, which creates an imbalanced decision-making environment. In the context of the motivation of this research established in Section 1, this exacerbates the ability for stakeholders to agree upon the best balance amongst the system outputs in a tradeoff hyperspace. Given these considerations, stakeholder misalignment may be further impeded if there is disproportionate "voting power" or importance amongst stakeholders. Situations where this may exist include hierarchical decision-

56

making environments such as those observed in many businesses and organizations today that have tiered employment structures. If there is disproportionate power or influence amongst stakeholders, this adds an additional, competing dynamic to resolving stakeholder misalignment.

4.3.4. Facilitating Stakeholder Alignment

If stakeholder misalignment is identified using the Tradeoff Analysis Framework, the framework might in turn be used to facilitate stakeholder alignment. A few approaches for doing this are mentioned hereafter and are offered as complementary insights for how to facilitate stakeholder alignment. The common objective of these approaches is to increase stakeholder alignment relative to the system output tradeoffs under consideration. As stated in Section 4.3.3, this may be achieved through stakeholders having a common preference structure directionality/sign or form, or, in the case where value is very sensitive to the preference structure, this may require the stakeholders to have very similar preference structure values or forms, depending on the valuation method used. An important consideration for facilitating stakeholder alignment is the number of stakeholders and stakeholder preference diversity. As the number of stakeholders grows along with the diversity of their respective preferences, achieving stakeholder alignment is likely to become more difficult.

<u>OPTION 1: SUPRA-OBJECTIVE FUNCTION</u>

The first potential option for facilitating stakeholder alignment is to use a supra- (or meta-) objective function. The general form of this function is given in Equation 5 and it encompasses all of the individual stakeholder value functions (and hence preference structures).

Equation 5

$$\text{Value}_{\text{Supra}} = \sum_{\forall j} \Lambda_j \cdot V_j$$

In Equation 5, Value$_{\text{Supra}}$ is the supra-objective value function and it is the sum of all individual stakeholder value functions, V_j, multiplied by their respective relative weighting factors, Λ_j. The weighting factors are a measure of relative importance amongst the stakeholder value functions and thus may be inferred as the relative "voting power" amongst the stakeholders. Typically, the weighting factors are normalized such that they sum to 1.0 to keep the weighting distribution on a convenient scale, but this does not have to be the case. Additionally, with this approach, stakeholders may use different valuation methods and thereby have different preference structure forms, the caveat being that all stakeholder value functions must map to the same value scale to keep the supra-value in one consistent unit.

The advantage of a supra-objective function is that once derived, there may be an opportunity to optimize the design and operation of system relative to this singular criterion, namely the supra-objective function shown in Equation 5, which accounts for all individual stakeholder value functions. This supra-objective function therefore provides the convenience of truncating all stakeholder value functions into one supra-value function, however, the major disadvantage of the supra-objective function approach for facilitating stakeholder alignment is best reflected through Arrow's "General Possibility Theory" [63]. The General Possibility Theory, in part, concludes that aggregating multiple stakeholder preferences (*e.g.,* via a supra-objective function) cannot be done without forcing stakeholders to compromise their own preferences, at least in some capacity, in order to create this social "welfare" function. Thus, while a supra-objective function is convenient, it often represents a compromise for every stakeholder and thus is always suboptimal for each stakeholder in terms of maximizing his or her value.

OPTION 2: NEGOTIATIONS

Another potential technique for resolving stakeholder misalignment is negotiation and the Tradeoff Analysis Framework may be used to facilitate such negotiations. For resolving tradeoff hyperspaces, negotiations may be of use in one of two fashions. First, negotiations may be used to find an amenable preference structure such that all stakeholders agree upon the same balance amongst the system tradeoffs. Thus, this approach relies of negotiations within the valuation component of the Tradeoff Analysis Framework. If this achieved, it effectively creates a single, unified stakeholder and corresponding value function. This negotiation approach therefore centers on discussions in the value (preference) structure space before the framework is ever executed. Conversely, the second usage of negotiations is centered in the system output space as generated with the Tradeoff Analysis Framework corresponding to a set of proposed changes. In this case, stakeholders may still disagree as to the right balance amongst the system output tradeoffs, and therefore have different preference structures, but the negotiations take place after the framework is executed and the system output/solution space is populated. In this case, negotiations are centered on the system output/value space and ensuing trades are made amongst the stakeholders as to amenable solutions in this space. This approach is different than the previously mentioned use of negotiations where negotiations are used to decide on a unifying preference structure, which would make the latter type of negotiations in the system output/value space unnecessary.

Negotiations are not guaranteed to lead to agreement amongst stakeholders, but through actively using negotiations within the Tradeoff Analysis Framework to learn about and refine stakeholder preferences, much can be gained in terms of achieving stakeholder alignment. As negotiations of the second type (*i.e.,* in the system output/value space) take place, negotiations of the first type (*i.e.,* for finding a common preference structure) will implicitly take place as stakeholder's compromise their own preferences in working towards finding an equilibrium in the system output/value space with the other stakeholders. There are many structured approaches for facilitating stakeholder negotiations and these belong to the domain of decision analysis and the methods developed in this field may serve as a useful starting point for facilitating multi-stakeholder negotiations. Some of these methods include: Game-Theoretic Methods, Automated Multi-Attribute Negotiation Methods, Interactive Decision Maps, Multi-Criteria Decision Analysis, Eclectic Multi-Criteria Analysis, and Multi-Actor, Multi-Criteria Analysis [20–23,64–69]. Section 2.2.6 specifically shows an example of using Game Theoretic methods to structure stakeholder negotiations.

OPTION 3: ANALYTICAL METHODS

The third potential approach for facilitating stakeholder alignment is the use of analytical methods within the Tradeoff Analysis Framework. The objective of using analytical methods is to identify and quantify how closely aligned stakeholders are with regard to their preferences and the system outputs. In doing so, analytical methods may help to identify the system output dimensions that will be easiest to align stakeholders along, or provide other constructive information for facilitating alignment, depending on the method used. Details as to potential methods that may useful in the framework are not discussed herein since the potential applicability of analytical methods varies considerably depending on the application of the framework. However, an example of the use of analytical methods to explore stakeholder alignment can be found in one of the case studies, specifically in Section 8.4.4, although this remains an active area of research for the framework development.

OPTION 4: MINIMUM ACCEPTABILITY THRESHOLD

The fourth potential approach for facilitating stakeholder alignment is to use minimum acceptable value (or system output) thresholds to guide the decision-making process. This approach requires eliciting the minimum acceptable value threshold from each stakeholder, and thus proposed changes offering less than the value threshold of a given stakeholder are unsuitable options (solutions). This approach therefore

effectively sets value constraints via the stakeholders and isolates the proposed change (solution) region(s) above every stakeholder's respective minimum value threshold. The caveat to this approach is that each stakeholder must assume the same preference structure (see CBA limitation discussion in Section 4.3.2). A simplified example of this approach for facilitating stakeholder alignment is conceptually depicted in Figure 4-14 where, given the two stakeholder
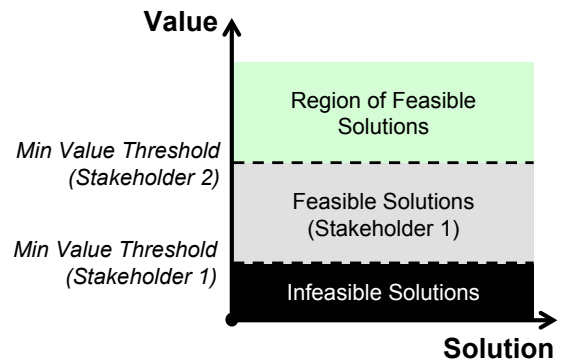
Figure 4-14. Stakeholder Value Thresholds.

minimum acceptable value thresholds, the region of feasible solutions (*i.e.,* proposed changes) that is acceptable to both stakeholders can be isolated. While these suitable solution regions are not guaranteed to exist, if they do, they provide rich opportunities for negotiation amongst stakeholders as to amenable solutions given the proposed change space. It should also be noted that this approach is not mutually exclusive with the previously mentioned supra-objective approach because this similarly isolates the regions of feasible solutions given a set of stakeholder value functions.

4.3.5. Stakeholder Value

Within the Tradeoff Analysis Framework, specifically the valuation component, there may be uncertainty with regard to stakeholder value. This source of uncertainty can arise when a stakeholder adopts a given valuation method and its respective preference structure but they are unsure about their preferences for a given system output with this structure. For example, if the uniform-additive, cost-benefit function is used (see Section 4.3.2), a stakeholder may be unsure of their value for a given weighting factor (λ). The aforementioned value uncertainty scenario may ultimately arise because of latent stakeholder preferences and subsequently helping them discover their latent preferences might be a facilitated through the following two uses of the framework.

INFERRING STAKEHOLDER PREFERENCES

In situations when stakeholders are unsure of their preferences for the system outputs, it might be possible to use the Tradeoff Analysis Framework to infer their preferences, given an assumed underlying preference structure. A simple example of an approach that might achieve this using the framework is as follows. This approach infers stakeholder preferences through allowing them to become the analyst in the framework and they therefore propose a change to the system given some reference, or starting proposed change. After

60

proposing a change, the resulting system outputs are conveyed to them in the system output space relative to that of the reference point in the space. An example of this is conceptualized in Figure 4-15 where the two system outputs corresponding to an alternative proposed change made by a stakeholder is shown relative to that of reference proposed change in the
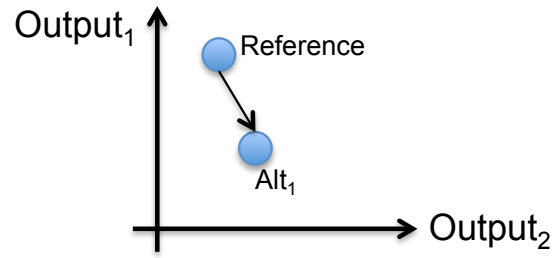
Figure 4-15. Sequence of Proposed Changes.

system output space. One potential means for inferring relative stakeholder preferences given the selection of a new proposed change is shown in Equation 6, which assumes the simple two-system output space shown in Figure 4-15. In Equation 6, Y_i^j is the jth system output corresponding to the ith alternative (proposed change) and P_k is the kth preference form (or value).

Equation 6

$$\frac{P_1}{P_2} \propto \frac{\left|Y_2^1 - Y_1^1\right|/Y_1^1}{\left|Y_2^2 - Y_1^2\right|/Y_1^2}$$

If a stakeholder proposes a change relative to some arbitrary reference proposed change, the corresponding balance amongst the system outputs corresponding to this change might be assumed to reflect their relative preferences for the system outputs. Their relative preferences for the outputs can then be inferred by computing the ratio of change in system output magnitude for each output relative to the datum system outputs, which correspond to the reference proposed change. This is shown in Equation 6 where the numerator is the absolute difference between system output 1 for the reference and new proposed change in Figure 4-15, relative to system output 1 for the reference proposed change. This numerator is then divided by the equivalent ratio for system output 2, given the reference and new proposed change. This overall ratio may then be inferred to be the stakeholder's relative preferences for the system outputs considered. And with this information, it may then be possible to use this ratio to determine what the stakeholder's preference structure values are, given some assumed preference structure. A specific example of using the Tradeoff Analysis Framework to infer a stakeholder's preferences can be found in the first case study results (see Section 6.4.2). It is also important to note that in this example the hypothetical stakeholder only proposed one change but in reality this process of inferring stakeholder preferences can be repeated with each new proposed change made by a stakeholder, given some reference proposed change.

An alternative approach for determining stakeholder preferences may be to isolate their value indifference points. In this approach, the goal is to evaluate changing stakeholder behavior due to incentives/policies enacted via the valuation component of the framework. This approach assumes some underlying preference structure for a stakeholder and then certain preference structure values (or forms) are changed. When this happens, the corresponding stakeholder-perceived, value-optimal design and/or operation of the system may change. The result of continually changing certain preference structure values (or forms) and, observing the corresponding change in a stakeholder's behavior, may eventually isolate the stakeholder's preference (or value) indifference points. These points will then possibly define regions of constant stakeholder behavior (*i.e.,* the perceived most valuable proposed system change) relative to the preference structure. A simple example of an approach to analyze stakeholder behavior would be to impose a tax on the design and operation of a system and determine how much of a tax is required to change a stakeholder's preferred design/operation of a system. This example is explored in further detail in the first case study in this research (see Section 6.4.2).

4.3.6. Uncertainty

It is important to recognize sources of uncertainty in the Tradeoff Analysis Framework. There are three potential sources of uncertainty in the framework and these ultimately lead to uncertainty in the value proposition. These sources of uncertainty are highlighted in Figure 4-16 and they include the system, external factors, and valuation. The first two sources arise from ambiguity
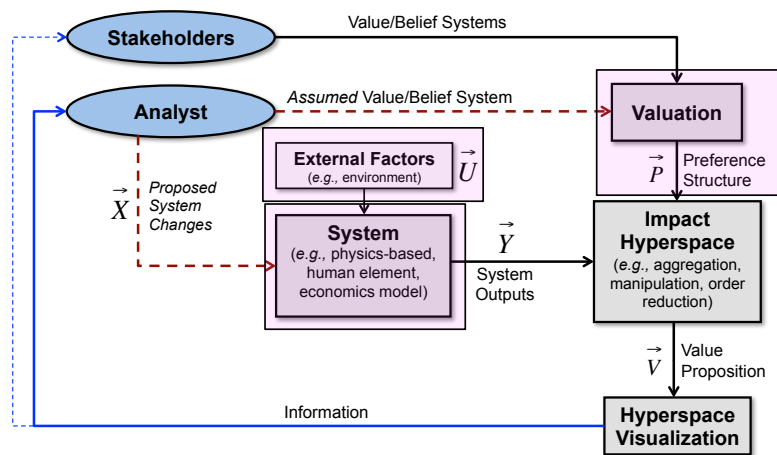
Figure 4-16. Uncertainty in the Framework.

in the system (*e.g.,* a model) and external factors (*e.g.,* the system's operating environment). Since the system is a representation, or abstraction of the system of interest, it is often a theoretical model, which will always have some uncertainty associated with it that may be relevant to address when implementing the framework. Additionally, there may be ambiguity in the external factors, in particular because they often

define the "real-world" operational context of a system, which can be difficult to capture theoretically and quantitatively. And the third potential source of uncertainty in the framework is the valuation component of the framework. The basis for this source of uncertainty depends on the valuation method employed, but uncertainty in valuation typically arises due to: an inability for stakeholders to accurately convey their preferences to a third party (see Section 4.3.5); a valuation method's manifestation of these preferences; and, if applicable, the various time-dependent assumptions used in valuation methods dependent on time-based forecasts (refer to Ref. [52]).

There are several implications of uncertainty in the framework. The first is the effect of uncertainty on the execution of the framework. Uncertainty effects value and this should be captured and conveyed in the value proposition generated by the framework, which, as a result may require a different execution (or adaptation) of the Tradeoff Analysis Framework. This implication is best addressed through answering the question of what, if any, changes need to be made in the framework to account for sources of uncertainty in the value proposition. An example of modifications made to the Tradeoff Analysis Framework in order to address uncertainty, specifically within the system and external factors in the framework is discussed in Section 8.5.2. The second implication of uncertainty in the framework is representing value. Uncertainty may create challenges in succinctly conveying the value proposition to the analyst and stakeholders. For example, if a random sampling method is used to capture uncertainty in the external factors, then a given proposed change may correspond to a large number of system output samples, and this may require a different approach for visualizing value as compared to instances where value is certain (*i.e.,* known deterministically). The remaining implication of uncertainty in the framework is adapting the framework to capture uncertainty in stakeholder value. There are several potential adaptations, or uses of the framework that can help capture this unique source of uncertainty and these are discussed in detail in Section 4.3.5.

4.4. Summary of the Tradeoff Analysis Framework Functionality

Given the breadth and depth of the Tradeoff Analysis Framework discussion in Section 4, the overarching framework functionality is summarized hereafter to serve as a reminder of the key attributes of the framework. The framework provides a formal construct for…

1. Analyzing the tradeoffs associated with change in designing new systems, or making modifications to existing systems in the context of stakeholder value.

2. Optimizing system design and operation using stakeholder value.

3. Analyzing the sensitivity of stakeholder value and the system outputs to the proposed system changes.

While the framework has capabilities beyond these three overarching functionalities, these capture the most important attributes of the framework and are important to keep in mind during the framework applicability evaluation, which is the topic of Sections 6-8.

5. OVERVIEW OF THE CASE STUDIES

In order to evaluate the applicability of the Tradeoff Analysis Framework discussed in Section 4, several case studies are employed that analyze the tradeoffs associated with changes in aerospace system design and/or operation. Here, the tradeoffs are defined by the system outputs in the framework and the impact is the resulting value proposition. The case studies were selected to explore different aspects of the framework functionality in order to develop unique insights about the framework and its respective implementation. In addition, the case studies were chosen to provide a representative sampling of real tradeoff problems in the aircraft and space system domains as well as in terms of system maturity, specifically by applying the framework to analyze hypothetical (theoretical) systems as well as currently operational (mature) systems. The case studies sequentially increase in complexity in terms of the applying the Tradeoff Analysis Framework and the type and magnitude of changes in a system analyzed ith the framework. A brief overview of the case studies is presented hereafter.

CASE STUDY 1: SINGLE STAKEHOLDER, SIMPLIFIED AIRCRAFT CRUISE OPERATIONS (SECTION 6)

The first case study is the simplest and it examines the impact of changing aircraft cruise operations. In this case study, the emphasis of change is along the ConOps axis in the Change Taxonomy (see Figure 4-4). Although the relevant stakeholders in this case study include airlines, passengers, and the global community (since the environmental impacts of aviation affect everyone in some capacity), only the airline stakeholder is considered in the analyses. In this case study, the benefit of aircraft cruise operations is assumed uniform so the value proposition for the airline stakeholder only consists of the costs associated with operations. The subsequent airline value is derived from characteristics related to the operation of aircraft.

CASE STUDY 2: MULTI-STAKEHOLDER, AIRCRAFT APPROACH PROCEDURES (SECTION 7)

The objective of the second case study is to evaluate the impact of changing aircraft approach procedures with an emphasis on resolving competing preferences amongst a set of stakeholders. Here, the systems of interest are currently operating commercial aircraft and changing their procedures (*i.e.,* ConOps innovation) is enabled through advances in aircraft technology, specifically the use of GPS to increase aircraft situational awareness. There are three stakeholders of interest in this case study, airlines, airports, and communities. The airline's value is derived from the operation of aircraft as well as any population noise exposure created from the aircraft. The airports value is similarly derived from population noise exposure but also the arrival (throughput) of aircraft. Lastly, the community stakeholder group provides a

polarizing perspective of value in this case study since they bear the cost of aircraft noise but do not directly benefit from their respective operation.

<u>CASE STUDY 3: MULTI-STAKEHOLDER, REMOTE SENSING SPACE MISSION</u> (SECTION 8)

The objective of the third case study is to assess the impact of innovation on remote sensing (earth imaging) mission spacecraft. Therefore, the dimensions in the Change Taxonomy are really axes of potential innovation in this case study. In this study, new spacecraft architectures called fractionated spacecraft are developed through innovation in technology. And ConOps innovation occurs in this case study through changes in the respective redeployment strategies of spacecraft performing the mission. This case study is therefore more complex than the previous two in terms of the type and magnitude of changes analyzed that belong to the Change Taxonomy. The two stakeholders of interest in this case study are the spacecraft developers and operators, the former being responsible for developing the spacecraft and the latter being responsible for operating and managing the spacecraft. The value propositions for these two stakeholders differs in that the spacecraft developer does not receive any direct benefit from a spacecraft's operation other than having a successful mission whereas the operator directly benefits from the function of the spacecraft in terms of capturing images of the earth.

6. CASE STUDY 1 – SINGLE STAKEHOLDER, SIMPLIFIED AIRCRAFT CRUISE OPERATIONS

The first case study applies the Tradeoff Analysis Framework to analyzing the tradeoffs associated with commercial aircraft cruise operations. This case study therefore emphasizes changes in operations and not technology in the Change Taxonomy. The ensuing tradeoff hyperspace analyzed in this case study is specifically created from the following system outputs of interest for cruise operations: flight time, fuel burn, CO_2 emissions, NO_x emissions, contrails, and time in turbulence. This case study is the simplest examined because only changes in operations are considered and, additionally, only the airline is considered as a stakeholder in the analyses. This section begins with a brief background for the case study and then provides an overview of the Tradeoff Analysis Framework as applied to analyzing the tradeoffs associated with aircraft cruise operations.

6.1. Background

The cruise operations phase of an aircraft's flight is the portion of flight between a given origin (O) and destination (D) airport occurring after initial ascent and before final descent and landing. Often aircraft will fly the great circle route during cruise, which is the geometrically shortest path between the O and D airports. In this phase of flight, aircraft are allowed to operate at a certain altitude, which for many commercial aircraft is around 33,000 ft. There are several stakeholders that may be of interest to consider for aircraft cruise operations, which includes airlines, airports, pilots, passengers, and regulatory bodies. Given these potential stakeholders, interesting environmental-performance tradeoffs include reducing flight time at the cost of higher CO_2 and NO_x emissions.

6.2. Literature Review – Case Study 1

There have been several works in the literature that have evaluated the impact of changes in cruise operations, specifically the environmental-performance tradeoffs associated with operations. These investigations have predominantly been lead by Kroo from Stanford University and Waitz from MIT [70–74]. Their work has collectively focused on the detailed modeling, evaluation, and tradeoff exploration of aircraft climate impacts in the context of performance-based tradeoff dimensions. The first two studies led by Kroo are similar and they specifically examine aircraft cruise operational tradeoffs such as that amongst operating costs, emissions, landing and takeoff (LTO) NOx emissions, and noise. Then in 2008, Kroo led another study, specifically resolving the tradeoff amongst operating costs, NO_x emissions, CO_2 emissions, and route demand for commercial aircraft cruise operations. Kroo's studies resolved competing tradeoff

67

dimensions through optimizing a supra-objective (tradeoff) function embodied in a tool called PASS [70–72]. The most recent study from Kroo was published in 2009 and is unique because of its inclusion of a climate impact model, which quantifies the global temperature response from aircraft engine emissions and contrails [73]. The tradeoff dimensions in this study were again optimized using PASS and included metrics such as global temperature change, cost, fuel burn, and NO_x emissions.

Waitz led MIT's most focused research on evaluating the tradeoffs associated with aircraft operations [74]. This study specifically used a low-speed aerodynamic model and trajectory simulation to quantify the tradeoffs associated with cruise operations including that amongst performance (altitude and climb time), environmental impact (noise and emissions), operating costs, and noise. An optimizer was employed to redesign an aircraft's respective configuration and operation such that it provided the most value, given the optimizer's objective function of the aforementioned tradeoff parameters.

There has also been research looking at specific cruise route, or path optimizations, balancing both environmental- and performance-related tradeoff dimensions. In 2010, Campbell performed studies with the objective of reducing the environmental impact of aircraft operations by changing their respective in-flight paths (trajectories) [75]. The tradeoffs specifically considered were contrail formation, fuel cost, performance (trajectory profile and flight time), and disturbance avoidance as manifested by avoiding static and dynamic, hard and soft, no-fly zones. Analogous to the work at Stanford University and MIT, these tradeoffs were resolved through the use of an optimizer and therein a single objective function.

Lastly, there have been complementary works in the literature investigating environmental and performance tradeoffs for aircraft cruise operations for the Climate Compatible Air Transport (CATS) System and Aviation Integrated Modelling (AIM) Project [76,77]. The work on the CATS System was published in 2009 and it specifically analyzed aircraft cruise operations by considering the tradeoffs amongst: engine technology (capability), contrail formation, performance, and mission parameters such as time; this study also investigated the impact of the temporal and uncertainty aspects of cruise operations [76]. The second study, published in 2010, used the AIM project's Aviation Technology Module (ATM) to assess the tradeoffs amongst cruise altitude, fuel burn, and NO_x emissions [77]. Unlike the Stanford and MIT studies, these two works articulated the relevant tradeoffs associated with cruise operations but did not resolve competing tradeoffs via an optimization algorithm.

6.3. Application of the Framework

This section details the application of the Tradeoff Analysis Framework in this case study and begins with an overview of the framework followed by discussing each framework constituent in more detail.

6.3.1. Framework Application Overview

The application of the research framework in this case study is depicted in Figure 6-1. In this case study, the analyst inputs a cruise operation/trajectory given the O-D airport pair considered. The proposed change is then analyzed with Piano-5 and an aircraft performance post-processor (see Section 6.3.6), which collectively generate the system
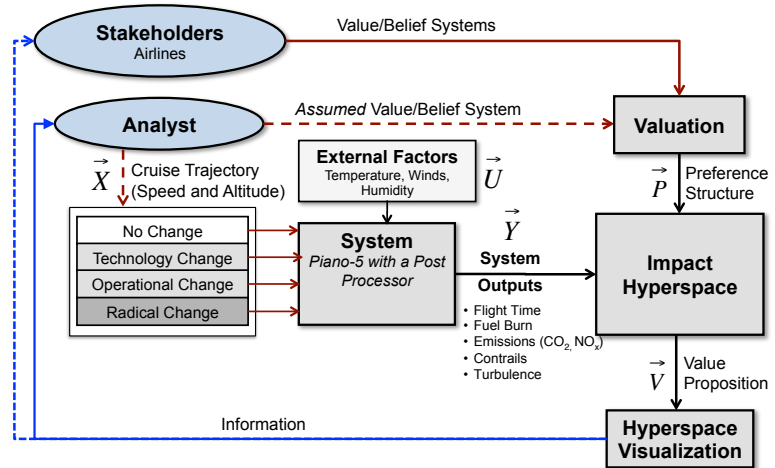
Figure 6-1. Framework Application (Case Study 1).

outputs of interest, which includes the cruise flight time, fuel burn, emissions, contrails, and turbulence. The external factors affecting the system include temperature, winds, and humidity. The only stakeholder considered in this case study is the airline, whose value is directly impacted by all of the system outputs.

6.3.2. Stakeholders and System Outputs

For this case study, the stakeholders of interest include the airlines, passengers, and the global community but only the airline stakeholder is considered in the case study analyses. The ensuing system outputs of interest to this stakeholder are shown in Figure 6-2 and as follows: **flight time** in units of hours (hrs), **fuel burn** in units of gallons (gals) or pounds (lbs), **CO_2 emissions** in units of kilograms (kg) or metric tons (mt), **NO_x emissions** in units of kilograms (kg) or metric tons (mt), **length of contrails produced** in units of (nm), and **time in turbulence** in terms of hours (hrs). Since there are six system outputs, this leads to a six-dimensional output, or tradeoff hyperspace to be analyzed in the case study. Flight time, fuel burn, CO_2 emissions, and NO_x emissions are that accumulated over the entire cruise trajectory. The contrail production is the cumulative length of contrails that a given aircraft produces during cruise. And the turbulence is the time spent in a given turbulence severity region during cruise, which is prorated by severity level ('none' (0), 'light' (3), or 'moderate or greater' (6)). The system outputs are computed for a single aircraft cruise trajectory.

	Flight Time (hrs)	Fuel Burn (gals, lbs)	CO₂ (kg, mt)	NOₓ (kg, mt)	Contrails (nm)	Turbulence (hrs)
Airline	🔴	🔴	◑	◑	🔴	🔴

Direct	🔴 Cost	🔵 Benefit	Indirect	◑ Cost	◐ Benefit

Figure 6-2. Stakeholder and System Output Matrix (Case Study 1).

As will be discussed in Section 6.3.3, the benefit of flying is assumed uniform in this case study, so the value proposition for the airline only consists of the costs associated with each system output. As seen in Figure 6-2, the airline directly incurs all of the direct costs associated with the system outputs because the aircraft is responsible for yielding all of these outputs. In addition, in this case study, the airline is assumed to also incur the indirect costs associated with aircraft emissions, as these costs are assumed a hypothetical tax that the aircraft has to pay if producing emissions. Thus, collectively, the airline bears the cost associated with all six system outputs considered in this case study.

6.3.3. Valuation

The valuation approach used in this case study is the uniform-additive, cost-benefit function described in Section 4.3.2. The only difference in this case study is that the benefit of flying is assumed to be uniform for the airline, so value equals cost as is shown in Equation 7. Since the time scale associated with the system output quantifications for a given cruise is small (*i.e.,* on the order of hours), discounting is negligible and value in this case study therefore becomes:

Equation 7

$$Value = Cost = \sum_{i=1}^{n} \left(\lambda_i \cdot Y_i \right)$$

In Equation 7, *Value* is equal to cost, so all value results reported in this case study are negative. In the equation, $Y_{i,}(t)$ is the ith system output and $\lambda_{i,}$ is the ith uniform preference weighting corresponding to the ith system output, respectively. λ_i will be negative since the system outputs considered in this case study are all costs.

PREFERENCE STRUCTURE

The airline stakeholder has a "λ-Set" that translates their respective costs into their value proposition, given the uniform-additive, cost-benefit function used in this case study. The stakeholder λ-Set is defined in Table 6-1 along with reference values for each λ; note that the λ's are all negative since they correspond to system outputs that are costs.

λ_{DOC}	λ_{Fuel}	λ_{CO2}	λ_{NOx}	$\lambda_{Cont, AP}$	$\lambda_{Turb, AL}$
Operating cost	Fuel cost	Social cost of emissions		Cost of producing contrails	Turbulence cost penalty
-1164 $/hr	-2.49 $/gal	-0.04 $/kg	-4.05 $/kg	-0.10 $/nm	-10.00 $/hr

Table 6-1. Reference λ-Set (Case Study 1).

In Table 6-1, current values were used for the hourly operating cost of an A320-200 and the price of Jet-A fuel [78,79]; note that the operating cost does not include the cost of fuel since this is a separate system output. The social costs of CO_2 and NO_x emissions are based on recommendations from an Interagency Working Group and a university study [80,81]. And, there are presently no recommendations for the social cost of contrails and turbulence cost penalty so reasonable reference values were assumed for these respective λ's, recognizing that there may be significant uncertainty in these values.

6.3.4. Proposed System Changes

The analysis emphasis in this case study is changing aircraft cruise operations (ConOps) using *currently available* commercial aircraft (without modifications), thus Technology and Radical Changes are not analyzed the case study (see Figure 6-3). In this case study, changes in ConOps specifically occur through changing the specific cruise operation used. The baseline cruise route used for
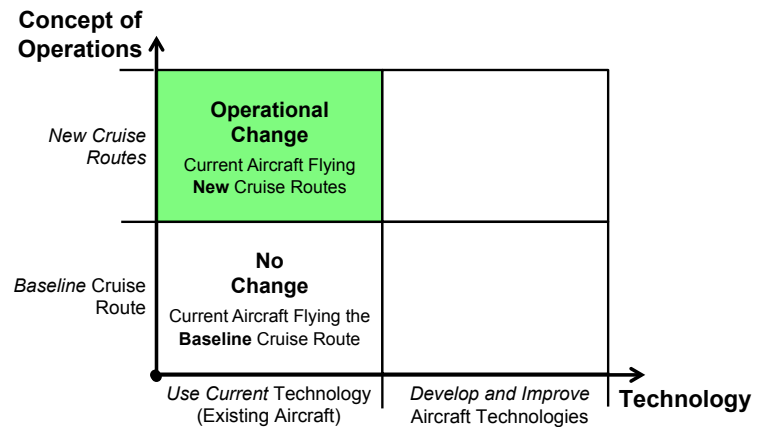
Figure 6-3. Change Taxonomy (Case Study 1).

comparison is the cost-index optimal route for the airline, which corresponds to the optimal cruise route when the airline incurs the cost of flight time and fuel burn but does not incur the cost associated with any

other system outputs in this case study. Therefore, in relation to the reference λ-Set shown in Table 6-1, the baseline route is the value-optimal route corresponding to the direct operating costs and cost of fuel. Given the simplified cruise operations setup discussed in Section 6.3.5, all departures from the cost-index optimal route will be explored, however, of particular interest is comparing the cost-index optimal route with optimal route corresponding to the reference λ-Set shown in Table 6-1. This route will correspond to an airline that cares about cost of operating aircraft along with the adverse environmental impacts of aircraft operations as reflected in the system outputs in this case study.

6.3.5. System Model: The Simplified Model of Aircraft Operations

In order to fully explore the space of cruise operations, a deliberately simplified version of the cruise portion of a flight is considered where aircraft must enter and exit the cruise environment at FL290 (the initial climb and final descent phases are not considered). The cruise leg of interest in the case study is that between the LAX and JFK airports where LAX is the origin airport; this cruise leg has a corresponding distance of 1800nm. The cruise trajectories only vary in the vertical (*i.e.,* flight level) direction along the cruise leg (see Figure 6-4) where there are seven potential altitude transition points at 257nm intervals. There are then five potential flight levels (FL) along this leg at 2 kft intervals. The rates of aircraft climb and descent between any altitude transitions are fixed at +/-100 ft per min, respectively. The simplified representation of a cruise trajectory results in a total of 78,125 candidate
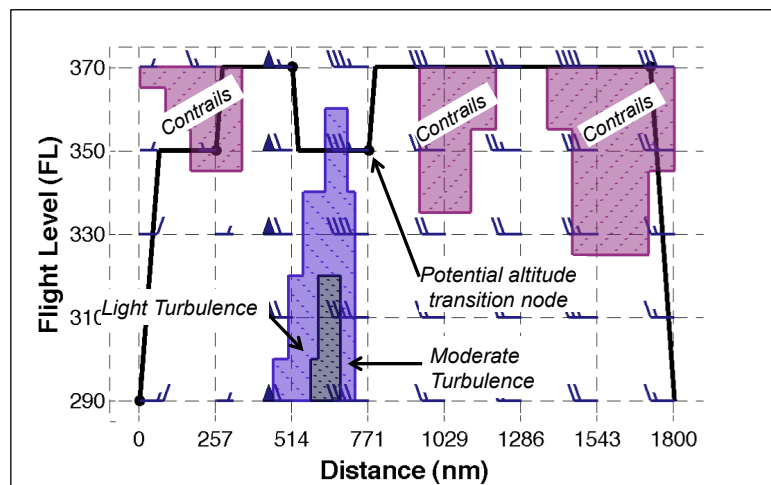
Figure 6-4. Simplified Cruise Operations Representation using the September 21, 2009 External Factors.

vertical profiles. And, in addition, aircraft fly at one of 21 constant cruise speeds along a given vertical profiles in the Mach range of [0.73, 0.85], leading to over 1.6 million possible cruise trajectories (*i.e.,* vertical profiles and speed combinations). Therefore, changes in ConOps in this case study entails changing the vertical cruise profile of an aircraft and its respective speed along that profile. The remaining simplification made in this case study is that only Airbus A320 aircraft are considered for cruise operations and the initial aircraft mass after initial ascent and before cruise is 164,889 lbs.

72

The system outputs corresponding to a given simplified cruise trajectory are computed with a model comprised of Piano-5, a professional aircraft modeling tool and a custom aircraft performance post-processor [82]. For a given cruise trajectory, flight time, fuel burn, and emissions are computed with Piano-5. Then, based on the cruise flight trajectory and external factors, the length of contrails produced and time in turbulence is computed by the post-processor, given the cruise environment setup shown in Figure 6-4. Since the contrails are geometrically represented in the cruise environment by "contrail regions," the length of contrails produced by an aircraft is simply the length of its respective cruise trajectory that passes through these contrail regions. Similarly, time in turbulence is the amount of time an aircraft spends in the turbulence regions given its respective cruise trajectory and speed. Since there are varying turbulence levels, time in turbulence is pro-rated by severity level to reflect a higher cost penalty for flying through more severe turbulent areas.

6.3.6. External Factor Model

The external factor (operating environment) for cruise operations varies by day. The external factors considered in the analyses performed in this case study are shown in Figure 6-4 and they correspond to a three-hour period on September 21, 2009. There are three external factors considered: winds, contrails, and turbulence. In Figure 6-4, the winds are represented using a vectored notation where at each mesh point a half-line, full-line, and triangle correspond to 5, 10, and 50kts, respectively, and, if the wind intensity notation is to the right or left of its origin (base) line, then it is a headwind or a tailwind, respectively. Aircraft will produce contrails if they fly in a contrail region and these regions are formulated using the Schmidt-Appleman criterion for contrails [83]. In the cruise environment, the weather data at altitude are populated by the Rapid Update Cycle (RUC) weather model [84]. And, lastly, the turbulence severity regions in Figure 6-4 are approximated from Graphical Turbulence Guidance (GTG2) data provided by the National Oceanic and Atmospheric Administration's (NOAA) Aviation Digital Data Service [85]. The GTG2 data categorizes
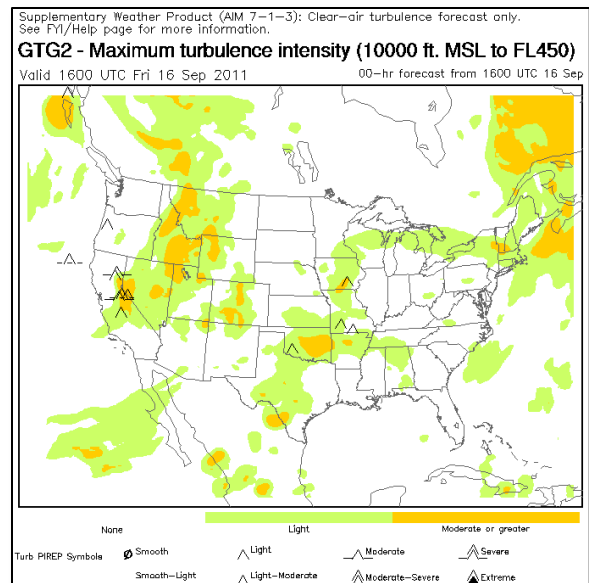
Figure 6-5. GTG2 Turbulence Data.
Source: NOAA's National Center for Atmospheric Research

73

turbulence on a severity scale of 'none,' 'light,' and 'moderate or greater' and the data is provided at discrete FL's as shown in Figure 6-5 where each severity level is shaded a different color. The GTG2 turbulence regions are extracted and mapped to the two-dimensional cruise leg (*i.e.,* along the great circle) between a given O and D airport as shown in Figure 6-4, thus giving rise to the turbulence "pillars" in this figure.

6.4. Analyses

This section presents the case study analyses, each of which provides a different perspective of applying the Tradeoff Analysis Framework in order to assess the impact of changes in aircraft cruise operations. The cruise route of interest is that between the LAX and JFK airports where LAX is the origin airport and the setup and assumptions for analyzing cruise operations along this is discussed in Section 6.3.5.

6.4.1. Overview of Analyses

Numerous analyses are performed in this case study and they collectively evaluate the No Change and Operational Change categories in the Change Taxonomy (see Section 6.3.4). The resulting analyses performed in this case study are as follows:

1. <u>Baseline Study</u>: This analysis evaluates the cost-index optimal cruise route for an airline, which corresponds to the value-optimal route when only the cost of time (direct operating costs) and the cost of fuel are considered (refer to Table 6-1 for the λ values used). In the results, this is trajectory is referred to as the Baseline trajectory. The corresponding value function for this route is given in Equation 8:

Equation 8

$$Value = Cost = -\lambda_{DoC} \cdot FT - \lambda_{Fuel} \cdot FB$$

In Equation 8, λ_{DoC} and λ_{Fuel} are the cost of time and fuel, respectively, and *FT* and *FB* are the system outputs of flight time and fuel burn, respectively.

2. <u>Operational Change Study</u>: In the operational change study, all possible perturbations from the Baseline cruise trajectory will be analyzed, which, given the simplified nature of the cruise reference problem (see Section 6.3.5), this leads to a total of 1,640,624 unique cruise operations (*i.e.,* vertical trajectory and speed combinations) to be analyzed in the Operational Change category. Of particular interest in this set of trajectories is that corresponding to the reference λ-set in Table 6-1, which corresponds to an airline that incurs the cost of every system output, given the reference values. This trajectory will be referred to as the Everything Trajectory in the analyses.

74

Therefore, in this case study a total 1,640,625 assessments will be conducted, thereby providing a unique perspective of the framework usage as compared to the other two case studies, namely, through the analysis and subsequent comparison of a very large number of proposed changes by the analyst in the framework.

6.4.2. Analyses and Results

Five different analyses are performed in this case study to analyze the tradeoffs associated with changing aircraft cruise operations. The first analysis in this case study explores the entire space of trajectories (proposed changes) using the Framework with Optimization. The purpose of this analysis is to gain an understanding of the entire system output space relative to the airline stakeholder cost-index optimal trajectory. The second analysis uses Principal Component Analysis to quantify and understand the global tradeoff trends amongst the system outputs given their enumeration in the first analysis. The third analysis compares the Baseline and Everything trajectories defined in the previous section. The fourth analysis in the case study demonstrates a unique application of the Tradeoff Analysis Framework in this research, namely, as a policy analysis mechanism. This analysis specifically uses the Framework with Optimization in order to evaluate changing airline behavior (*i.e.,* their perceived value-optimal cruise trajectory) given a changing hypothetical tax on aircraft-produced contrails as well as changing direct operating costs. And the fifth and remaining analysis uses the Tradeoff Analysis Framework to infer stakeholder preferences for the direct operating cost and cost of fuel, which are assumed unknown.

ANALYSIS 1 – EXPLORING THE SYSTEM OUTPUT SPACE

The first analysis employs the Tradeoff Analysis Framework to explore the entire system output space, which is possible because of the intentionally simplified cruise operation environment (see Section 6.3.5); this analysis thereby repeatedly executes the system transform described in Section 4.3.1 to populate the system output space. In this analysis, each proposed changes corresponds to a unique combination of system outputs contributing to this space. One of the goals of quantifying the entire output space is that it provides a constructive perspective for understanding the range of possible stakeholder value propositions given the valuation method employed in this case study. Of particular interest are comparing the Baseline and Everything Trajectories defined in Section 6.4.1. Additionally, the system output space will show the macroscopic trends in the system outputs, which may be constructive for understanding the underlying "behavior" of cruise operations as framed and modeled in this case study.

75

The result from evaluating all possible vertical (cruise) trajectories at the 21 different Mach numbers considered is provided in Figure 6-6. Figure 6-6 shows the entire system output space using a subplot visualization approach where the system output space is consistently plotted with respect to fuel burn and flight time and then color shading is used to convey the other four system outputs, each dedicated to its own subplot. This visualization approach was chosen because it keeps the output space directly comparable amongst the subplots, which is important for reflecting decisions made in one subplot to the others; thus, the plots can be directly compared given their common axes, but each provides a different perspective of the system outputs. Given the value function used in this case study (see 6.3.3), the cost-index optimal trajectory is noted in Figure 6-6 as "Baseline" and the optimal trajectory corresponding to the entire reference λ-set is noted in the figure as "Everything." Deviations from the Baseline trajectory demonstrate instances of changing aircraft cruise operations in order to improve in other system output dimensions, for example, such as reducing flight time as compared to the Baseline trajectory, which would correspond to trajectories in Figure 6-6 located to the lower right of the Baseline trajectory.
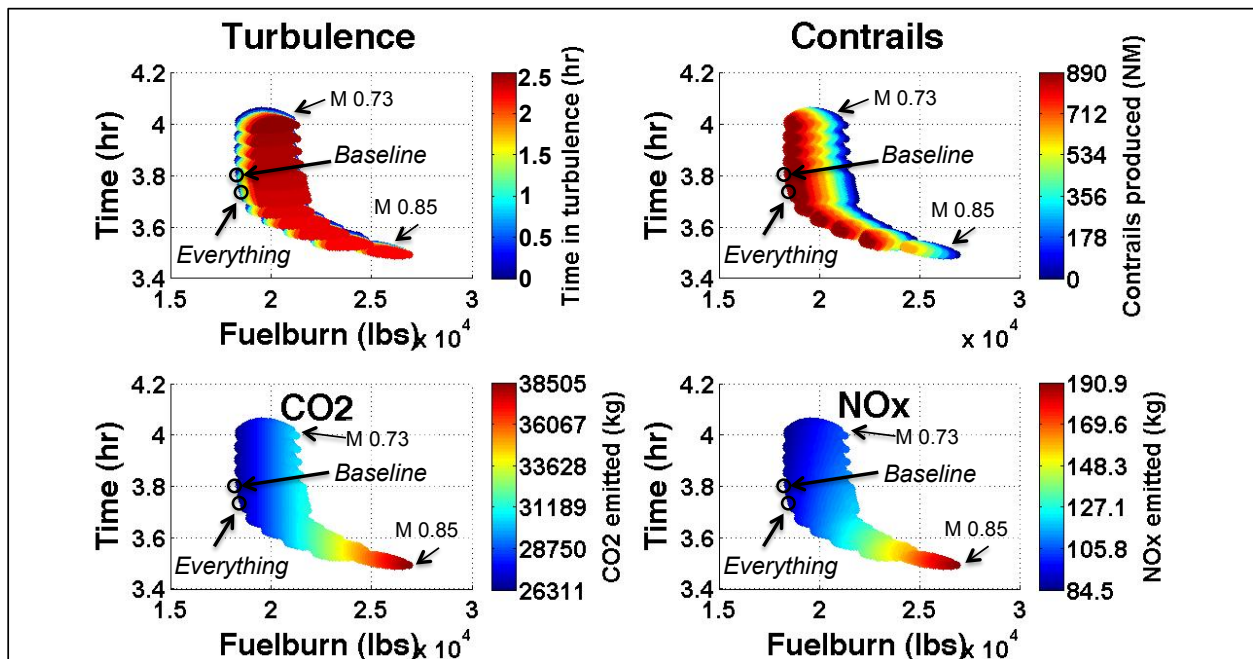
Figure 6-6. The Full-Factorial System Output Space.

In Figure 6-6, the distinct oblong groupings in the fuel burn-flight time space each correspond to all candidate vertical trajectories flown at one of the 21 possible cruise speeds. The oblong group vertically centered on a flight time of 4 hrs (*i.e.,* the top left group) corresponds to the slowest speed, Mach 0.73, while the group the furthest to the bottom and right corresponds to the fastest speed, Mach 0.85; hence,

76

the latter group has the lowest flight time. The oblong groups in the middle of Figure 6-6 between a flight time of roughly 3.6 and 3.7 hrs are closer together due to the refinement of the Mach speed mesh around the most common cruise speeds of Mach 0.77 to 0.79. Since contrail production is not affected by aircraft speed, all data groupings having a similar color gradient with respect to the contrails produced given the space of possible fuel burns, where the lowest contrail production is achieved at the cost of the highest fuel burn within a given group. This is due to the external factors assumed in this case study (see Section 6.3.6), specifically the contrail regions that are consistently located at the highest cruise altitudes, which also happen to be the most fuel-efficient altitudes to fly at. A similar observation holds for turbulence, although time in turbulence is slightly affected by cruise speed. Conversely, CO_2 and NO_x emissions are strongly dependent on fuel burn. CO_2 is directly proportional to fuel burn whereas NO_x is roughly proportional to fuel burn and flight time; hence, these two system outputs are correlated with the fixed axes of fuel burn and flight time in Figure 6-6.

A visualization of the system output space like that shown in Figure 6-6 provides useful insights about the tradeoffs amongst the six system outputs. For example, these plots clearly exhibit the general tradeoff between fuel burn and time: fuel burn increases as time decreases, and vice-versa. Given the representation of the system output space in Figure 6-6, some of the other tradeoff insights gained are the relatively high correlation of CO_2 and NO_x emissions with fuel burn, which was expected. Additionally, given the external factors assumed in this case study, it becomes apparent that reducing fuel consumption comes at the cost of higher contrail production, thus these are two important competing tradeoffs. Conversely, it appears that reducing fuel consumption also reduces the time passengers spend in turbulence so these two dimensions are actually complementary.

ANALYSIS 2 – TRADEOFF RESOLUTION USING PRINCIPAL COMPONENT ANALYSIS

In the second analysis, Principal Component Analysis (PCA) was used to determine the competing and complementary nature of the system outputs constituting the tradeoff hyperspace. PCA is a useful method for quantifying the correlation (or lack thereof) amongst the system outputs and representing the resulting system output tradeoff hyperspace in a reduced-order space [86]. This representation enables the most important system output tradeoffs to be readily identified, as will be demonstrated hereafter.

In this analysis, PCA was specifically used to analyze the data corresponding to all possible vertical cruise profiles (recall there are 78,125 of these) flown at their respective cost-index optimal Mach number. In

77

order to demonstrate the sensitivity of the system output tradeoffs to the external factors, this analysis is applied to two atmospheric cruise environments, the first represented in Figure 6-4 and the second in Figure 6-7.

The first step in this analysis was to use the Tradeoff Analysis Framework to analyze
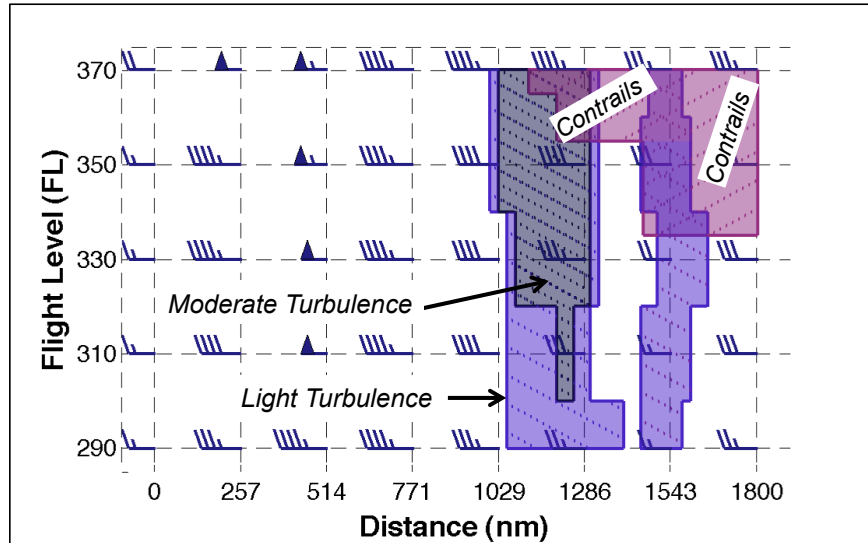
Figure 6-7. August 12, 2011 External Factors

all 78,125 vertical cruise profiles flown at their cost-index optimal Mach number for both external factor scenarios represented in Figure 6-4 and Figure 6-7. The resulting system output space was then analyzed by PCA. After applying PCA to the system outputs corresponding to all 78,125 vertical cruise profiles flown at their cost-index optimal Mach number, it was found that two principal components captured 99.99% and 99.85% of the variability in the system output space with the first and second external factor scenarios considered, respectively, implying that the original six-dimensional system output tradeoff hyperspace can be captured in a two-dimensional principal component space. Since this is the case, PCA effectively reduces the order of the original six-dimensional system output tradeoff hyperspace to two dimensions.

The two-principal component representation of the system output space corresponding to the two external factor scenarios is shown in Figure 6-8 and Figure 6-9; note that the space in these figures is normalized on the range of [-1, 1]. The scattered data in these figures is the system output space generated from
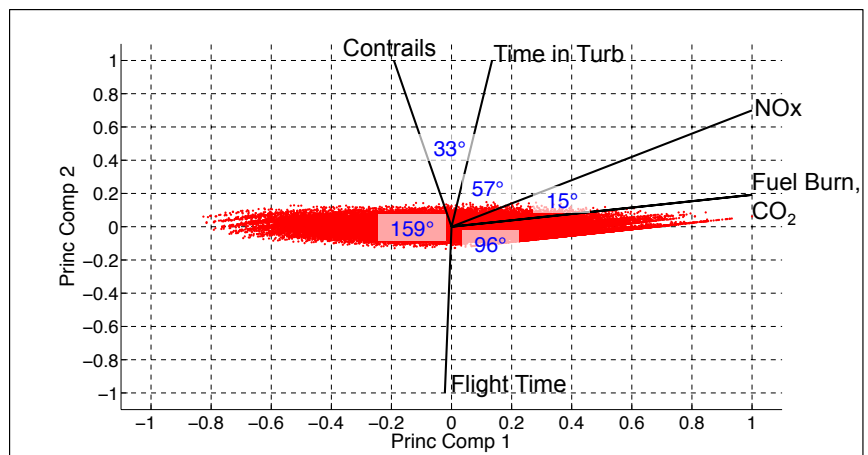
Figure 6-8. PCA Representation of the System Output Space (September 21, 2009 External Factors).

78

analyzing all possible cruise operations with the Tradeoff Analysis Framework for the two external factors considered. And the black lines are the ensuing tradeoffs amongst the six system output dimensions based on the system output space data. Along each black line, the corresponding system output
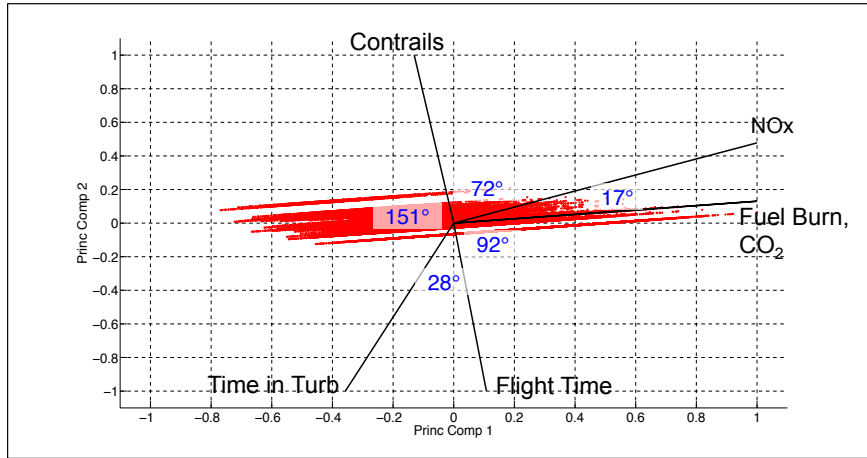
Figure 6-9. PCA Representation of the System Output Space (August 12, 2011 External Factors).

increases in magnitude while travelling away from the start of the line at the origin of the PCA plot, [0, 0]. The angular proximity of a given tradeoff vector to a principal component is indicative of its relative contribution to that principal component dimension; this is because principal components are composite variables of the six system outputs. For example, in Figure 6-9, fuel burn is fairly close in proximity to principal component 1 (*i.e.,* the x-axis), thus, it contributes proportionally the most to the first principal component dimension.

The relative angular displacement amongst the six output dimensions shown in Figure 6-8 and Figure 6-9 by the black lines can be used to determine the complementary and competing nature of these outputs in relation to one another. Specifically, as the angular offset between any two dimensions nears 0°, 90°, and 180°, the two outputs become perfectly complementary, neutral, and perfectly competing, respectively, *assuming* that an increasing magnitude in an output is more desirable. Complementary output dimensions are aligned such that increasing the value of one increases the value of the other, whereas competing dimensions (*i.e.,* tradeoffs) demonstrate the converse of this situation. And neutral output dimensions are uncorrelated.

Given the relative angular offsets amongst the dimensions in Figure 6-8 and Figure 6-9, several observations can be made about the system outputs corresponding to the cruise operations analyzed during the two days of atmospheric conditions considered in this PCA analysis. First, in Figure 6-8 and Figure 6-9, fuel burn and CO_2 emissions are parallel, so they are perfect complements and thus not tradeoffs with one another at all. This was expected since CO_2 emissions are directly proportional to fuel burn, regardless of weather

79

conditions. Additionally, in Figure 6-8 and Figure 6-9, NO_x emissions are complementary to fuel burn, however, this complementary nature depends, in particular, on the distribution of winds in the cruise environment, which varied between the two days of external factors considered (refer to Figure 6-4 and Figure 6-7). And in Figure 6-8 and Figure 6-9, the roughly orthogonal angle between the complementary "tradeoff" group of fuel burn/CO_2/NO_x -and- the contrails, flight time, and time in turbulence tradeoff dimensions, indicates that this complementary group is nearly uncorrelated with the latter three dimensions, which implies that this former group is neutral to (*i.e.,* a weak tradeoff with) the latter group of tradeoff dimensions.

The remaining observation about the PCA representations of the system outputs in Figure 6-8 and Figure 6-9 is the difference between the correlation, or lack thereof, amongst contrails, flight time, and time in turbulence, given the two days of weather analyzed. In Figure 6-8, the time in turbulence and contrails are found to be closely correlated (almost parallel), implying that as the time in turbulence increases, contrail length generally increases. This arises because the tailwinds are lighter at higher FL's, which also happens to be where the contrails are located. Hence, the trajectories passing through the higher FL's experience proportionally more time in turbulence and typically produce more contrails. The fastest trajectories are those predominantly at low FL's, where there are no contrail regions and where the time in turbulence is proportionally less because there are strong tailwinds. Hence, flight time is almost antiparallel to contrail production and time in turbulence. However, the previous observations regarding the relationship amongst contrails, time in turbulence, and flight time do not hold for the system outputs corresponding to the second day of weather used to analyze cruise operations, the PCA representation of this shown in Figure 6-9. In particular, the contrail and turbulence regions in the second weather scenario analyzed leads to a different tradeoff amongst these outputs. Since the turbulence and contrail regions are overlapping in Figure 6-7, this causes them to be closer to complementary than competing, which was not the case for the first weather scenario examined since the contrail and turbulence regions did not overlap. The remaining difference is that flight time opposes contrails and turbulence, which is the result of the fastest routes being at higher altitudes, thus reducing flight time comes at the cost of increased contrail production and time in turbulence since there are contrail and turbulence regions at high altitudes in this external factor scenario.

In summary, PCA is a useful method for synthesizing the system output tradeoff hyperspace and readily understanding the competing/neutral/complementary nature of the system output tradeoffs. It was found that fuel burn, CO_2, and NO_x are complementary but the competing/complementary nature of contrails,

80

flight time, and time in turbulence is dependent on the assumed external factors, or atmospheric conditions in which aircraft operate. Interesting future work might be to use PCA to quantify the system output tradeoff volatility to other key parameters such as the λ-set employed in this case study.

ANALYSIS 3 – COMPARING THE OPERATIONALLY DRIVEN AND OPERATIONALLY AND ENVIRONMENTALLY DRIVEN TRAJECTORIES

The system outputs between the operationally driven and operationally and environmentally driven trajectories are summarized in Table 6-2 and the comparison of their corresponding trajectories is shown in Figure 6-10. The operationally driven trajectory corresponds to the optimal trajectory when only the cost of time and fuel are incurred (*i.e.,* the cost-index optimal trajectory), whereas the operationally and environmentally driven trajectory corresponds to the optimal trajectory when the costs associated with all six system outputs is incurred. The cost-index (*i.e.,* operationally driven) optimal route happens to be the most fuel-efficient in the trajectory space,

System Output	Units	Operationally Driven (O)	Operationally and Environmentally Driven (OE)	ΔSystem Outputs (OE-O)
Flight Time		3hr, 44m, 25s	3hr, 47m, 6s	2m, 41s
Fuel Burn	gal	2735	2716	-19
CO_2 Emissions	kg	26658	26480	-178
NOx Emissions	kg	92.2	90	-2.2
Contrails Produced	nm	865	865	0
Time in Turbulence	hr	0.45	0.45	0
Cost of Trajectories	**USD**	**-11,164**	**-13,847**	

Table 6–2. Operationally Driven and Operationally and Environmentally Driven System Output Comparison.
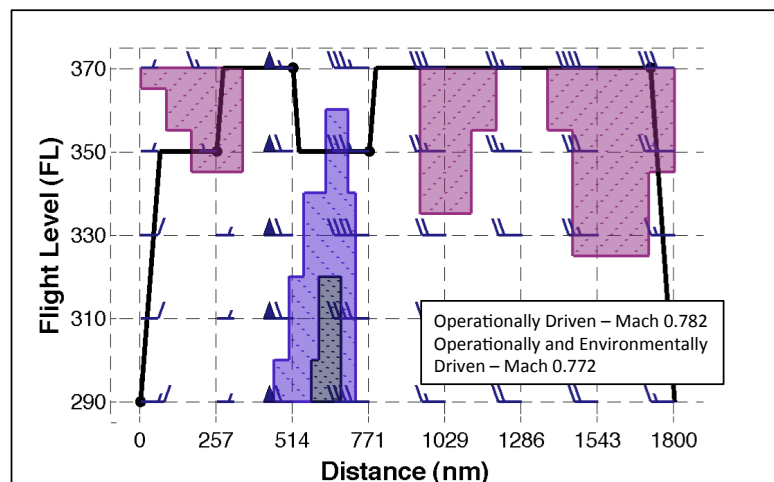
Figure 6-10. Operationally Driven and Operationally and Environmentally Driven Trajectory Comparison.

which also happens to pass through contrails and incur some time in turbulence. When the costs of the other system outputs are incurred, which corresponds to the operationally and environmentally driven trajectory, the same vertical trajectory is flown but at a slower speed, owing to the cost of emissions now being a factor in the airline's value function. Had the cost of contrails and time in turbulence been more dominate than the cost of time and fuel for the operationally and environmentally driven trajectory, the vertical trajectory would have been different than the operationally driven trajectory. However, given the operationally driven and operationally and environmentally driven trajectories, the slower speed of the operationally and environmentally driven trajectory as summarized in Table 6-2, leads it to have less fuel

81

consumption and emissions at the cost of a slightly higher flight time. The comparison of the operationally driven and operationally and environmentally driven trajectory system outputs therefore demonstrates an instance of a changing airline behavior, albeit a small change, in response to incurring the environmental impacts of cruise operations along with the cost of operations.

ANALYSIS 4 — THE FRAMEWORK AS A POLICY ANALYSIS MECHANISM

The remaining analysis in this case study uses the Tradeoff Analysis Framework as a policy analysis mechanism, thereby providing a unique demonstration of its potential utility to other tradeoff analysis problems. This analysis specifically uses the framework to assess how a hypothetical tax (cost penalty) on producing contrails, coupled with changing direct operating costs, alters an airline's perception of the best (*i.e.,* least expensive) trajectory. Thus, this analysis employs the Framework with Optimization where the analyst performs a sensitivity study on λ_{Cont} and λ_{DOC} and the four other λ-Set values are fixed to their respective reference values provided in Table 6-1. The result of this leads to the identification of the iso-optimal trajectory "behavior" regions for the airline as a function of λ_{Cont} and λ_{DOC}. For this analysis, the external factors are that shown in Figure 6-4.

The preference structure values explored in this problem are summarized in Table 6-3. The corresponding range of λ_{Cont} is from 0 \$/nm to that required to impose enough of a cost penalty (incentive) for airlines to completely avoid producing contrails, given the range of λ_{DOC} values. The λ_{DOC} values were varied from 70% to 130% of λ_{DOC} reference value in Table 6-1. Figure 6-11 shows the results from this policy analysis, which depicts the length of contrails produced by the optimal (*i.e.,* lowest cost) trajectory as a function of λ_{Cont} and λ_{DOC}.

λ-Set Definition		Units	Reference λ-Set
Direct Operating Cost	λ_{DOC}	\$/hr	From -900 to 1400
Cost of Fuel	λ_{Fuel}	\$/gal	-2.49
Social Cost of CO_2	λ_{CO2}	\$/kg	-0.04
Social Cost of NOx	λ_{NOx}	\$/kg	-4.05
Cost of Producing Contrails	λ_{Cont}	\$/nm	Decreasing from 0
Turbulence Cost Penalty	λ_{Turb}	\$/hr	-10.00

Table 6-3. Contrail Tax Study (λ-Sets).
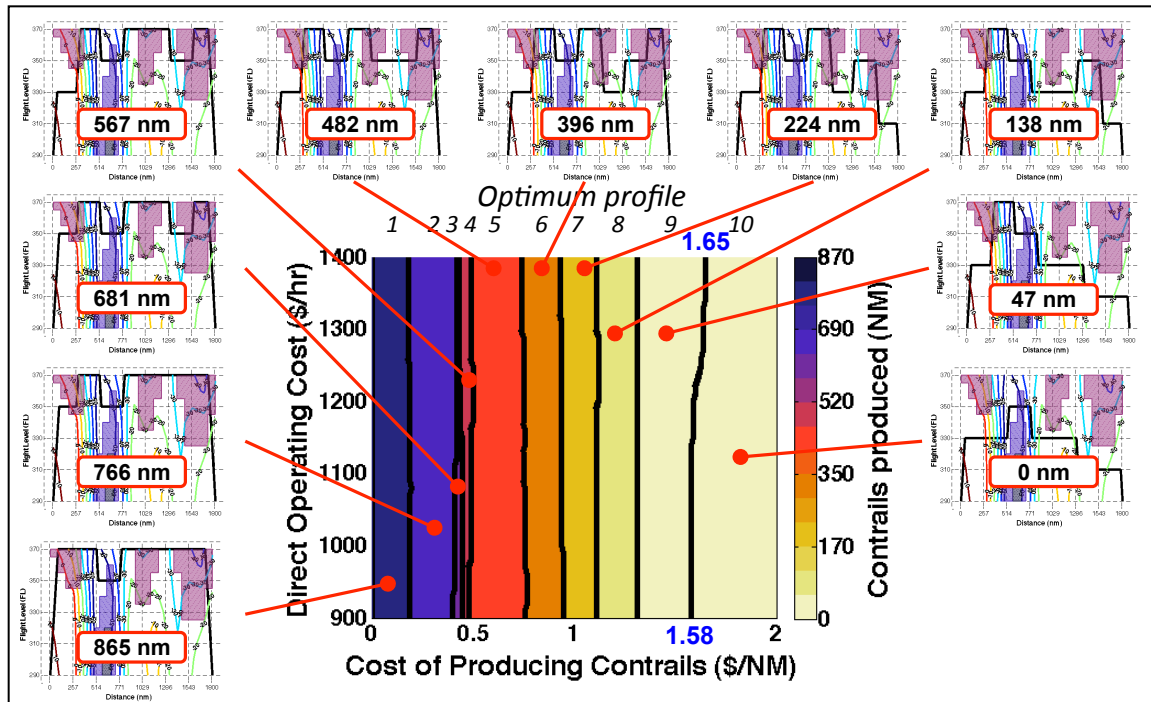
Figure 6-11. Results of the Contrail Tax (Policy) Analysis.

The results from the policy analysis summarized in Figure 6-11 show the discrete contrails regions in order of decreasing length of contrails produced in the positive x-axis direction. It is important to note that these results are highly dependent on the assumptions made in the case study, in particular, that these results only correspond to the day of weather assumed for cruise operations (see Sections 6.3.5 and 6.3.6). Additionally, the reason for the discrete contrail regions in Figure 6-11 is that the cruise trajectories and the contrail regions are both discrete functions of the distance along the cruise and FL, so contrail length is not a continuous function. The transition between iso-contrail regions in Figure 6-11 shows that as the hypothetical contrail tax increases, there will be a limit at which point the value (total cost) of the current optimal trajectory becomes too expensive given the contrails produced and is replaced with a new trajectory, which subsequently produces less contrails. Specifically, Figure 6-11 shows that when there is no cost penalty for producing contrails, the corresponding optimal trajectory produces 766 nm of contrails, the maximum amount (see Trajectory 1 in Figure 6-11), thereby flying the most fuel efficient cruise route. However, as the cost of producing contrails increases, trajectories with less contrail production become more preferable, until the cost of contrails becomes significant enough (*i.e.,* greater than 1.58-1.65 $ per nm) such that no contrails are produced by the airline's optimal trajectory. Avoiding contrails may, however, compromise the other systems outputs. For example, producing less contrails may lead to an

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increase in fuel burn or flight time, but this compromise is necessary in instances when the cost of producing contrails is sufficiently large due to the contrail tax. The results from this analysis thus confirm the intuition that when taxation is applied, the stakeholder perceived-optimal cruise operation, or behavior will eventually change if the tax becomes large enough (*i.e.,* a large enough incentive is imposed).

In the policy analysis example, there is also a coupling between the cost of contrails and flight time (*i.e.,* direct operating costs), in terms of defining the iso-contrail regions shown in Figure 6-11. Since λ_{DOC} affects the optimal cruise speed for a given trajectory, the flight time differs within a given iso-contrail region. In general, as λ_{Cont} increases, aircraft are incentivized to avoid contrails at the cost of increased flight time. Correspondingly, in Figure 6-11, each contour line has a slight slope, which is indicative of the relative difference in flight time between neighboring optimal trajectories. A contour line is negatively sloped if the neighboring trajectory with less contrails (*i.e.,* to the right) is on average faster. This arises because as λ_{DOC} increases, the operating costs become the dominant contributor to cost and hence, regardless of λ_{Cont}, there is more incentive to change to the faster trajectory with its lower operating costs. Conversely, if the neighboring trajectory to the right is slower, then as λ_{DOC} increases, there is more incentive to fly the current and faster trajectory and incur the cost of more contrails rather than increase operating costs by switching to the neighboring trajectory; this situation leads to the positively slope lines in Figure 6-11.

One extension of this policy analysis performed with the Tradeoff Analysis Framework would be to quantify the sensitivity of the optimal trajectory choice to uncertainties in the λ-Set since, for example, the λ_{Cont} range corresponding to each iso-contour region in Figure 6-11 is effectively an allowable uncertainty in λ_{Cont} within which the aircraft operation (*i.e.,* vertical trajectory) is not altered. This type of analysis is motivated in Section 4.3.5, which discusses methods for inferring and understanding stakeholder behavior even if they cannot articulate their respective preferences given the system outputs of interest. A simple demonstration of this follows.

Given the airline stakeholder in this case study, there may be situations when they do not know what their preferences are for all or some of the system outputs. If this is the case, it may be possible to use the Tradeoff Analysis Framework to infer their preferences, given some assumed preference structure such as the λ-Set in this case study. An example of doing this is pursued hereafter that relies on using the enumerated system output space shown in
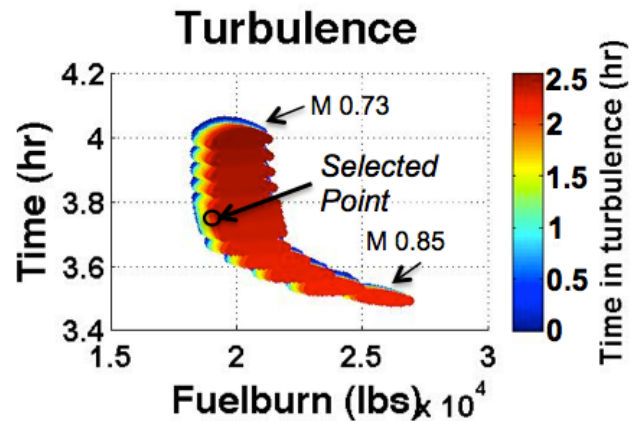
Figure 6-12. Airline Selected Point.

Figure 6-6. In this hypothetical scenario, the airline is assumed to be confident in their preferences, or λ values for CO_2 emissions, NO_x emissions, contrails, and time in turbulence and these are equal to their reference values in Table 6-1. They do not, however, know what their preferences are for the cost of time and fuel burn. In this situation, they select a given point in the system output space that seems like a desirable solution for them. This point is shown in Figure 6-12, which is the fuel-time and time in turbulence subplot in Figure 6-6. This point corresponds to a unique trajectory with a unique speed and thereby set of system outputs. Given these outputs and the known λ values for CO_2 emissions, NO_x emissions, contrails, and time in turbulence, the range of possible combinations of the λ for flight time and fuel burn that correspond to the selected trajectory can be determined. The specific method for achieving this is to use the framework with optimization in reverse (refer to Figure 4-3), namely, given a set of system outputs, determine the possible combinations of the λ-set that lead to the selected trajectory as being the optimum. In this simple example, only the cost of time and fuel are assumed unknown so the possible combinations of these leading to the selected profile need to be determined. The result of inferring the airline preferences in this simple
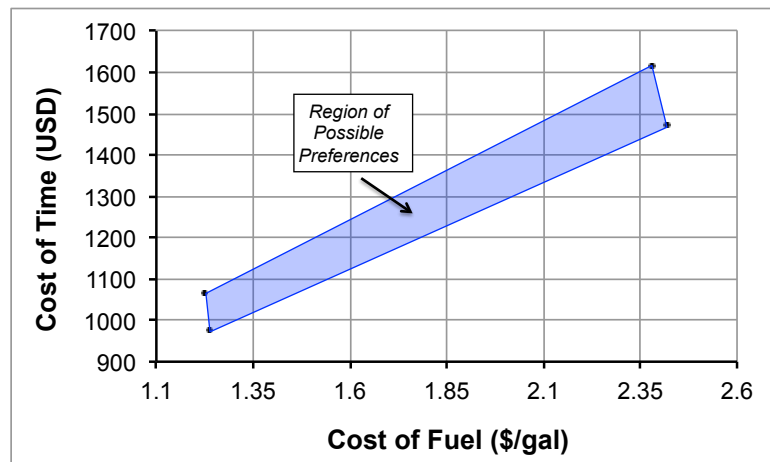
Figure 6-13. Region of Possible Airline Preferences.

85

example is shown in Figure 6-13, which depicts the region of possible airline preferences for the cost of time and fuel that correspond to the trajectory they selected in the system output space shown in Figure 6-12.

The advantage using the Tradeoff Analysis Framework to infer stakeholder preferences is that it may be possible to actually determine what their preferences are even if they cannot articulate them by allowing them to become the analyst in the framework and given some assumed preference, or valuation structure. In this simple example, the hypothetical airline stakeholder was unsure of their preferences for the cost of time and fuel so they selected a desirable trajectory in the system output space and then the framework with optimization was used (in reverse) to infer their preferences. The results of this are shown in Figure 6-13, which bounds the possible combinations of their preferences for the fuel and time, even though they could not articulate these. As seen in the figure, any point within the region of possible combinations corresponds to the possible preferences for the stakeholder with regard to the cost of the time and fuel. While this example was simplified to determining the airline's preferences for two of the system outputs, it can readily be extended to include the other system outputs considered in this case study. Therefore, this particular usage of the Tradeoff Analysis Framework to infer stakeholder preferences may be of great value when using the framework to determine appropriate values for preferences that are very uncertain such as the cost of contrail production, given some stakeholder and an assumed preference structure.

6.5. Discussion

The first case study examined the impact of changing aircraft cruise operations. Therefore, in this case study, the emphasis of change was along the ConOps axis in the Change Taxonomy (see Figure 4-4). ConOps change specifically occurred through altering aircraft cruise operations along a specific origin-destination route; in the case study, the cruise leg of interest was that between the LAX and JFK airports. The relevant stakeholder for cruise operations only included the airline and the benefit of cruise operations was assumed uniform, so their respective value proposition was simply the cost of cruise operations.

Given the aforementioned problem setup, the corresponding objective of this case study was to thoroughly explore the space of all possible cruise operations (trajectories) and, in doing so, understand the tradeoffs associated with changing cruise operations. Of particular interest was comparing the cost-index optimal trajectory with that corresponding to the full reference λ-set in Table 6-1. The subsequent case study analyses focused on three different facets of exploring the system output and value space using the

86

framework. The first focused on enumerating the entire system output space and understanding the ensuing tradeoffs amongst the system outputs. The second analysis focused on using the framework to understand the impact of a hypothetical contrail production tax on changing airline behavior as measured by their perceived-optimal cruise operation. And the last analysis used the framework to infer the airline's preferences, given the assumed preference structure in this case study. The specific insights gained from the case study about the impact of changing aircraft cruise operations will be discussed first followed by a discussion of the unique implementation insights gained from applying the Tradeoff Analysis Framework in this case study.

6.5.1. Case Study Insights

Several important insights were gained about the impact of changing cruise operations from the results of the study, each of which is discussed in turn. The first set of insights is with regard to the system output tradeoffs observed from the results and the second set of insights are those gained in using the framework as a policy analysis mechanism, as was done in the case study. And the last set of insights is about the results from inferring the airline's preferences using the framework. The remainder of this section then discusses the notable assumptions and limitations given the simplified model of cruise operations used for this case study, which remains an important consideration in interpreting the case study insights.

SYSTEM OUTPUT TRADEOFFS

One unique aspect of this case study was that a very large number of proposed changes were evaluated, which introduced challenges in understanding the impact (tradeoff) space and conveying this to the analyst and stakeholders. The first key insight gained in this study is that there are persistent tradeoffs associated with changing operations and these may be irresolvable. For example, in this case study it was found that the environmental impacts are often competing with the performance impacts of cruise operations such as that between reducing cruise (flight time) at the cost of higher CO_2 emissions. Of particular interest in this case study was comparing to cost-index optimal trajectory with that corresponding to the complete reference λ-set in Table 6-1. In the case of the cost-index optimal trajectory, the most fuel and time-efficient trajectory was flown, however, once the airline was forced to incur the cost of the environmental impacts of cruise operations, their new optimal trajectory burned less fuel than the cost-index optimal trajectory at the cost of having a higher flight time. While this is a simple comparison, it does demonstrate how airline behavior might be analyzed using the Tradeoff Analysis Framework to yield interesting insights

about their potential behavior (*i.e.,* cruise operation) in response to considerations beyond just the operating cost of an airline.

THE IMPLICATIONS OF POLICY FOR CRUISE OPERATIONS

The other insight gained in this study is the potential role and impact of a regulatory stakeholder in the Tradeoff Analysis Framework. To this end, the second analysis performed in this case study was used to quantify changes in the airline stakeholder behavior (*i.e.,* their perceived value-optimal trajectory) in response to a hypothetical tax on producing contrails, along with changes in their direct operating costs. This hypothetical imposition of a tax by an arbitrary regulatory body therefore evaluated one potential role of a regulatory stakeholder (policy enactor) in the Tradeoff Analysis Framework. The key result from the contrail tax study is that in order to supply sufficient incentive for airlines to entirely avoid producing contrails, an estimated tax of $1.58-$1.65 (per nm of contrails produced) must be imposed on aircraft, given the range of direct operating costs considered and the assumptions made in the case study. The cruise trajectories corresponding to this tax value range are departures from the cost-index optimal aircraft cruise route, thus supporting the argument that regulatory influence on the operation of aircraft is likely going to require changes in aircraft operations in order to meet the imposed regulations. The response to regulations via changes in operation is an important lesson learned from this case study in terms of one potential role and subsequent impact of a regulatory body in the framework. For example, even though cruise operations were intentionally simplified in this case study, the framework was used to provide a rough estimate of a tax of about $1.62 per nm of produced contrails in order to force airlines to completely stop producing contrails. However, it is important to recognize that this result is derived from analyzing cruise operations for one day with the corresponding external factors for that day. Therefore, this policy analysis application of the Tradeoff Analysis Framework may ultimately be a very constructive application of the framework for future and more detailed evaluations of the impact of potential aviation policies.

INFERRING STAKEHOLDER PREFERENCES

The last analysis in this case study was used to infer the airline stakeholder's preferences given the assumed preference structure. In this analysis, it was assume that the airline did not know, or could not articulate their preferences for flight time or fuel burn. Subsequently, the Tradeoff Analysis Framework was used to determine their preferences for these outputs by allowing them to select a suitable trajectory in the system output space. Then, given this trajectory, the range or possible combinations of the cost of time and fuel were determined that lead to the selected trajectory being the optimum. This analysis was therefore very

insightful about a unique usage of the framework, which may be of great use in future applications to determine stakeholder preferences even if they cannot articulate them.

While this case study yielded valuable insights into the impact of changing cruise operations, it is important to recognize a few limitations of the case study, which affect the implications of the insights previously discussed. First, the intentionally simplified representation of aircraft cruise operations may be overly simplistic to be prescriptive for commenting on the actual tradeoffs associated with aircraft cruise operation. Recall that aircraft cruise operations were constrained to only vertical changes in flight level at pre-specified points along the cruise leg. Coupled with the value function assumed in this case study, this simplistic representation of cruise operations enabled the cruise operations to be optimized for a given stakeholder. However, real aircraft cruise operations cannot be analogously simplified for optimization purposes without the loss of accuracy in the system representation. Thus, the insights gained in this case study conform to these limitations and this demonstrates a tradeoff in using the Tradeoff Analysis Framework to identify macroscopic trends in the system output/value space with less accuracy, via making simplifying assumptions and using a simple model, versus only investigating part of the potential system output/value space in more detail and accuracy, via avoiding such simplifying assumptions with a detailed model that may take more time to execute.

6.5.2. Framework Implementation Insights

This section discusses the insights gained about the execution of the framework through its respective application in this case study to assess the impact of changing aircraft cruise operations.

EXPLORING THE SYSTEM OUTPUT TRADEOFFS WITH PRINCIPAL COMPONENT ANALYSIS

Principal Component Analysis (PCA) was used to quantify the competing and complementary nature of the six system outputs of interest in this case study. As discussed in its application in Section 6.4.2, PCA can be used to represent the hyperspace of system output tradeoffs in a reduced-order space, which provides a simplistic, or lower-order representation of the relative correlation, or tradeoffs amongst the outputs of interest. PCA achieves this by mapping the system output space to a n-dimensional principal component space, where n is often less than the order of the original system output space. A principal component is a composite variable of the original six system output dimensions and selecting the number of principal components depends on the amount of variability in the system outputs captured by the principal

components. The particular manner in which PCA can be used to identify the complementary and competing nature of the system outputs is by representing the tradeoff dimensions in angular proximity to one another in a reduced-order space, given the space of system outputs analyzed with the Tradeoff Analysis Framework; here, the output dimensions increase in magnitude along the respective dimension from the origin in the PCA representation. Specifically, as the angular offset between any two dimensions nears 0°, 90°, and 180°, the two outputs become perfectly complementary, neutral, and perfectly competing, respectively, *assuming* that an increasing magnitude in an output is more desirable. Complementary output dimensions are aligned such that increasing the value of one increases the value of the other whereas competing dimensions (*i.e.,* tradeoffs) demonstrate the converse of this situation. And neutral output dimensions are uncorrelated, or independent.

The information provided from PCA, specifically in terms of readily identifying the most competing and complementary system outputs provides several benefits to the analyst in the Tradeoff Analysis Framework. First, it identifies the most competing system outputs, which represent the most import tradeoffs that need to be resolved, or balanced in order to decide on the best design and operation of a system. While these important tradeoffs can be determined without using PCA, in comparing Figure 6-6 with Figure 6-8 and Figure 6-9, the tradeoffs are much easier to identify with the latter figures produced via PCA. In particular, this is because all of the tradeoffs are represented in a two-dimensional rather than six-dimensional space and that the angular proximity of the system outputs in the PCA space allows an analyst to put quantifiable numbers on how competing and complementary the outputs are, relative to the assumed external factors. The second advantage of using PCA, which is implicit to using it to identify the most important tradeoffs amongst the system outputs, is that the most complementary outputs are identified. These complementary outputs demonstrate instances of partial or full system output alignment and, in the case of perfectly complementary outputs, this effectively reduces the number of tradeoffs in a hyperspace that need to be resolved. Even with close, but not perfectly complementary outputs, these outputs offer opportunities for stakeholders who may initially have different preferred balances amongst these outputs to potentially achieve alignment with respect to these outputs.

One of the interesting usages of the Tradeoff Analysis Framework in this case study was as a policy analysis mechanism, which did not require any modifications to the framework. As a policy analysis mechanism, the framework was used to observe changing stakeholder behavior in response to policy. The important implementation insight that arose from this usage of the framework is the role of a regulatory stakeholder in the framework. As considered in the case study, the regulatory body enacted policy via the valuation component of the framework, specifically via value-based incentives manifested by the preference structure. This thereby demonstrates one potential usage of the Framework with Optimization where the relationship between value-based incentives and the corresponding optimal proposed changes is explored. The specific manner in which this worked was that the assumed regulatory stakeholder incentivizes changing stakeholder behavior by deliberately changing the magnitude of the assumed preference structure (in this case study analysis, a uniform-additive, cost-benefit preference structure was used). Then as the magnitude of the preference structure changed, the perceived-optimal, or most desirable design and operation of the system for a given stakeholder also changed. The resulting relationship between stakeholder behavior and value-based incentives developed was at the crux of learning in terms of evaluating the implications of policy for the stakeholder(s) of interest. For example, as applied herein, the framework was used to determine the relationship between a tax on contrails and the corresponding most valuable proposed change (*i.e.,* cruise trajectory) for the airline. The result of this was determining the relationship between the optimal cruise operation for the airline and the tax on contrails, as summarized in Figure 6-11. While a contrail tax may be one potential future regulation in aviation, there is also presently an increasing emphasis on regulating aircraft emissions through a tax on CO_2 emissions [87]; currently, discussions are centered on what carbon-based metric should be used to quantify and thereby regulate carbon emissions. One potential option for regulating carbon emissions is to tax these emissions, so using the Tradeoff Analysis Framework to provide an estimate for the relationship between a tax on carbon emissions and the corresponding emission-production behavior of airlines may prove valuable for regulators/policy makers; a conceptual example of this relationship between aircraft emissions and the level of taxation is depicted in Figure
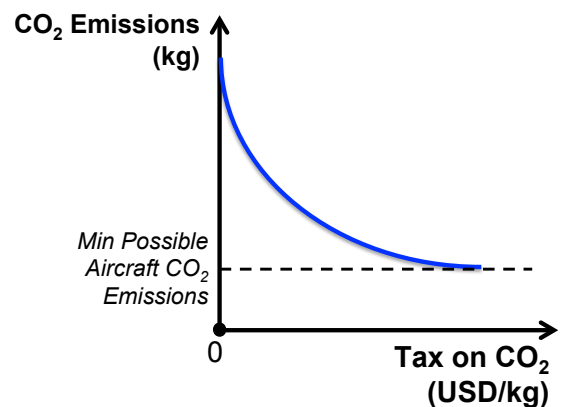
Figure 6-14. Policy Analysis Example.

91

6-14 assuming that a sufficient number of potential aircraft operations are modeled to provide the continuous trend shown in the figure.

As previously motivated, the application of the Tradeoff Analysis Framework as a policy analysis mechanism may be useful in a myriad of other applications. The key assumption made in using the framework as a policy analysis mechanism herein is that policy is enacted via value (or value-based incentives). However, this represents only one potential role of a regulatory body, or stakeholder in the framework. There may be other manifestations of policy elsewhere in the framework (*e.g.,* as a constraint) and thereby roles of a regulatory stakeholder. Therefore, in thinking about using the framework as a policy analysis mechanism, it requires the consideration of what type of policy is being introduced and how this can be manifested and therein enacted in the framework. For example, a regulatory stakeholder could directly regulate the design and/or operation of a system through the proposed changes rather than through taxation. Regardless, if using the framework as done herein where the policy is enacted via valuation, one limitation to recognize is that the absolute *value* of proposed changes cannot be compared due to the different underlying value functions when a tax (*e.g.,* a tax on contrails) is changed. Despite this limitation, the outcomes of this study still demonstrate a few important framework implementation insights. First, it may be possible to use the framework to isolate a given stakeholder's value-based incentive thresholds relative to their behavior (*i.e.,* perceived value-optimal system design and/or operation). Second, it might be possible to use the framework to infer stakeholder value-based indifference points given the current system design/operation of interest. And third, it might be possible to use the framework to determine the most important value-based couplings that drive the perceived-optimal design and/or operation of a system. Correspondingly, the use of the Tradeoff Analysis Framework as a hypothetical policy evaluation mechanism remains a rich area for future exploration and discovery.

STAKEHOLDER PREFERENCE INFERENCE

Another useful application of the Tradeoff Analysis Framework explored in this case study is to use it to observe stakeholder behavior and subsequently infer their respective preferences. As mentioned in Section 4.3.5, one potential source of uncertainty is in valuation, specifically if stakeholders are incapable of eliciting their respective preferences for the system outputs (or tradeoff dimensions). This is a concerning source of uncertainty since the role of valuation in the framework is important and uncertainty in this valuation can thereby diminish the utility of the overall framework. Using the framework to infer

92

stakeholder preferences may be one option for helping to resolve this source of uncertainty, even though the stakeholder may never be able to directly elicit their preferences. This unique usage of the framework relies on using the framework, except in reverse. In this case, the stakeholder of interest becomes the analyst in the framework and is thereby allowed to propose changes to the system. Given a proposed change and the corresponding system outputs, the framework can then be used to determine the range of possible preferences for these system outputs, given an assumed preference structure. The specific method for achieving this is to use the framework with optimization in reverse (refer to Figure 4-3), namely, given a set of system outputs, determine the possible combinations of the λ-set that lead to the selected trajectory as being the optimum. In the simple example pursued in this case study, the cost of time and fuel were assumed unknown so the possible combinations of these preferences leading to a selected profile by the airline stakeholder were determined. This usage of the Tradeoff Analysis Framework may therefore be of use for future analyses with the objective of determining stakeholder preferences even if they cannot elicit them.

The important attribute of the framework that arises from the last two insights, that is, using the framework as a policy analysis mechanism and as preference inference mechanism, is that the Baseline Tradeoff Analysis Framework can be adapted, extended, and used to potentially solve a multitude of different real problems in engineering.

7. CASE STUDY 2 – MULTI-STAKEHOLDER, AIRCRAFT APPROACH PROCEDURES

The second case study applies the research framework to analyzing the impact of changes in commercial aircraft approach procedures, which is enabled through equipping aircraft with GPS. The corresponding stakeholders of interest in this case study include the airlines, airports, and communities surrounding the airport of interest. Given these stakeholders, the system output hyperspace analyzed in this case study is comprised of flight time, fuel burn, CO_2 emissions, NO_x emissions, throughput, and population noise exposure. Therefore, this case study is more complex than the first one since multiple stakeholders with different preferences are considered and also because the changes in both technology and ConOps are considered. This section begins with a brief background on aircraft approach procedures and then follows with the application of the Tradeoff Analysis Framework in this case study.

7.1. Background

The objective of this case study is to use the Tradeoff Analysis Framework to analyze the environmental-performance tradeoffs (*i.e.,* impact) associated with changing aircraft approach procedures. Unlike cruise operations, which are largely relegated to a fixed altitude throughout cruise, approach procedures offer opportunities to significantly manipulate operations. Of interest in this case study is changing approach operations using Required Area Navigation and Performance (RNAV/RNP) procedures, which are enabled by GPS technology; these procedures are briefly discussed hereafter and a more extensive discussion of RNAV and RNP can be found in Muller [88]. RNAV is specifically responsible for creating point-to-point speed and direction directives largely independent of Navigation Aid Systems (NAVAIDs) located on the ground, whereas RNP specifies the required level of navigation performance, or accuracy; hence, RNAV/RNP approaches may be fairly freeform. Conversely, current conventional aircraft approaches follow Instrument Landing System (ILS) procedures, which rely on aircraft using ground-based NAVAIDs to guide them into landing, therein creating a fixed point-to-point system for regulating aircraft approaches. Consequently, conventional approach procedures are a combination of speed and position directives often resulting in long straight-in legs, inefficient routes, and suboptimal terminal airspace usage. However, given that RNAV/RNP approaches may have many degrees of freedom, which can result in RNAV/RNP routes being more geometrically complex, they offer opportunities to better optimize a given terminal airspace usage relative to a comparable ILS approach. The reason for the increased freedom with RNAV/RNP routes is that aircraft capable of using these routes must be equipped with GPS, which provides them with increased situational awareness through more accurate positioning and speed data

95

relative to that possible with present aircraft and, thus, GPS-equipped aircraft can fly more complex routes, if desired.

Some benefits of GPS-equipped aircraft flying RNAV/RNP routes also includes increased airspace density through allowing aircraft to fly close in proximity (via reduced inter-aircraft separation distances) as well as not having to rely on NAVAIDs, but rather GPS, to guide their respective approaches. Therefore, the resulting RNAV/RNP routes can be more freeform and only require periodic radio check-ins with air traffic control (ATC), and this allows for RNAV/RNP approaches to be tailored to a given airport terminal airspace, which may in turn lead to complex-curvature approach legs to avoid obstacles, minimize noise exposure, and so forth – something not achieved with many present day ILS approaches.

RNAV and RNP both specify levels of required aircraft performance in a given airspace. For RNAV performance, RNAV-X implies that an aircraft will not deviate from its flight path laterally and horizontally by X nm for 95% of the total flight time; the lateral buffer is shown in Figure 7-1 [89]. Intuitively, lower -X values will require higher RNAV precision. RNP performance is analogous to RNAV performance in terms requirements for navigating a given airspace. For example, RNP-

Figure 7-1. RNAV-X.

1 is often used in low-density air traffic situations whereas RNP-0.3 and lower is used for high-density, controlled aircraft approach operations. Thus, RNAV-X/RNP-Y effectively creates a region, within which an aircraft is supposed to be safely controlled and avoid conflicts with other aircraft and objects while executing a specific procedure (*e.g.,* an approach).
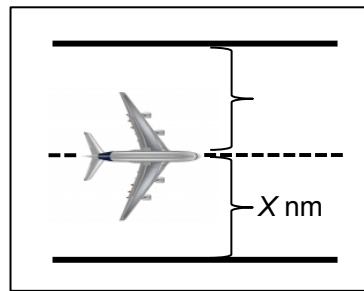
Several studies suggest that there are additional benefits from the capability provided by RNAV/RNP for aircraft operations than those previously mentioned, including reduced operational costs (fuel and time), increased runway capacity (via dual runway usage), and reduced interference from balked flights [90–92]. Another potential benefit of RNAV/RNP approaches is reducing the required separation distance between aircraft, which can lead to an increase in throughput at airports or reduced arrival delays. Lastly, in particular relevance to this case study, RNAV/RNP approaches provide the potential to mitigate community noise exposure around airports through tailoring approach routes to avoid densely populated areas.

7.2. Literature Review – Case Study 2

Previous research has assessed the potential benefits and costs of using RNAV/RNP approach procedures in place of ILS approaches. In reference to the motivation of this case study, considering noise impacts due to changing operations is important and there have been two key demonstrations of this. Alaska Airlines pioneered the use of RNAV/RNP given the often "terrain-challenged" airports they service, along with the highly variable weather at these airports [88]. Additionally, the airports serviced by Alaska Airlines often have limited ground navigation infrastructure, sometimes not even having a control tower. In the early 1990's Alaska Airlines began equipping aircraft with GPS and by 1994 they were using RNAV/RNP approaches. The result of this is that from 1994 to 2006 Alaska Airlines: prevented 1,300 (14.4%) of their flights from being cancelled; saved over 250,000 gallons of fuel; increased on-time performance; and significantly lowered the noise exposure to 750,000 residents in critical noise corridors [88].

These aforementioned observed benefits from RNAV/RNP ultimately became part of the motivation for assessing the impact of RNAV/RNP approach procedures at the Seattle-Tacoma (SEA) airport. Muller *et al.* performed a detailed assessment of the potential benefits of RNAV/RNP approaches at SEA, specifically comparing ILS and hypothetical RNAV/RNP approach procedures into SEA from the south, where the majority of the arrival traffic originates [93]. The results from Muller's study demonstrate that, given the geography of the greater Seattle area, RNAV/RNP approach procedures can be appreciably shorter than ILS approaches, thereby saving fuel and reducing aircraft emissions, and also reduce noise exposure to residents in Seattle relative to the noise exposure caused by ILS approaches. Thus, this study found that RNAV/RNP approaches are a win-win situation aside from any safety concerns, which were not addressed in the study. This research also concludes that using RNAV/RNP to increase conformance to existing ILS procedures provides a marginal benefit, and therefore the noticeable benefits of RNAV/RNP are realized from RNAV/RNP-optimized procedures, which may be appreciably different than ILS procedures.

Related works have also developed continuous descent approach procedures assuming the use of RNAV/RNP to further abate noise from the surrounding communities. The first of these works solely focused on noise reduction as the measure of success for a given approach procedure, resulting in insightful noise tradeoff quantifications associated with changing procedures via RNAV/RNP [94]. The second of these works developed a tool called NOISHHH, which optimizes aircraft approach trajectories with a multi-objective function comprised of flight time, number of awakenings (noise proxy), and fuel burn (emission

proxy) [95]. Lastly, the Enhanced Trajectory Prediction Model (ETPM), which is four-dimensional aircraft trajectory optimization model, was developed to optimize aircraft cruise phases in terms of altitude while minimizing their ecological impact as measured through CO_2 emissions and contrails [96]; the ETPM can also optimize the climb and descent phases of an aircraft's respective operation.

In the relevant literature, there are several works that provide approaches and methods to resolve competing tradeoffs associated with aircraft operations, which may be applicable to this case study. Some of these works support the use of multi-objective optimization algorithms to manage a variety of tradeoffs amongst aircraft design, performance, and environmental-related objectives [70,71,73,74,97–99]. Additionally, the Aviation Environmental Tools Suite (AETS) developed by the Federal Aviation Administration (FAA) is one of the more extensive tools focused on analyzing and resolving environmental tradeoffs for air transportation systems and has thus developed approaches for resolving tradeoffs associated with such systems [100]. And, lastly, in the domain of aircraft demand forecasting and traffic management, research has assessed tradeoffs amongst certain modes of transportation as well as options for resolving airspace conflicts [101–106].

7.3. Application of the Framework

This section details the application of the Tradeoff Analysis Framework in this case study and begins with an overview of the framework followed by discussing each framework constituent in more detail.

7.3.1. Framework Application Overview

The application of the research framework in this case study is depicted in Figure 7-2. In this framework application, the analyst first proposes an aircraft, runway (RWY) to approach, and the throughput along that approach. The analyst then selects a type of change to consider and thereafter the specific approach procedure to implement. The system is therefore a specific
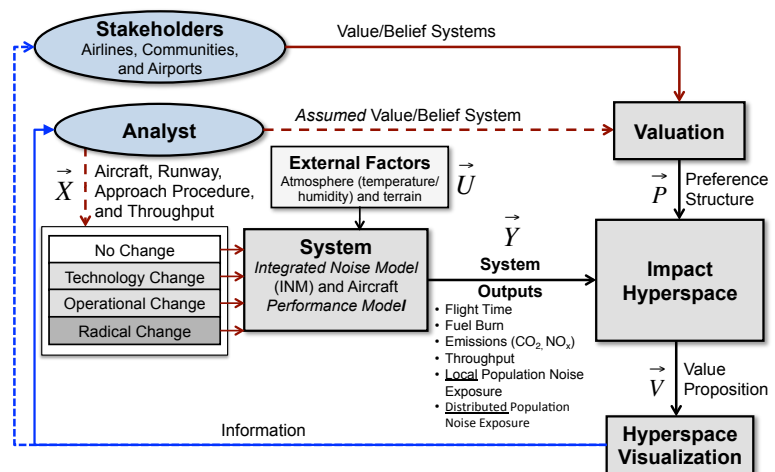
Figure 7-2. Framework Application (Case Study 2).

approach procedure (operation) consisting of four elements: a ground track, and an altitude, thrust, and speed versus ground track (distance) profile. A given approach is then analyzed with the Noise and Performance Impact Model (NPIM) described in Section 7.3.5, which consists of the Integrated Noise Model (INM) and a custom-built aircraft performance post-processor (model). The corresponding outputs of INM include noise contours and specific flight performance information, which is then input to the post-processor in order to compute the remaining system outputs of interest. The external factors affecting the system are internal to the NPIM and they include airport atmospheric conditions as characterized through pressure, temperature, winds, and humidity. The emphasis in this case study is on resolving competing stakeholders and the stakeholders of interest include the airline, airport, and community.

7.3.2. Stakeholders and System Outputs

There are multiple stakeholders of interest in this case study and these include the airlines, airports, regulatory bodies, passengers, and communities near the airport. However, in the study only the airline, airport, and community stakeholders are considered. Given these stakeholders, the system outputs of interest are shown in Figure 7-3 and are as follows: **flight time** in units of hours (hrs); **fuel burn** in units of gallons (gals); **CO_2 emissions** in units of kilograms (kg) or metric tons (mt); **NO_x emissions** in units of kilograms (kg) or metric tons (mt); **population noise exposure** in units of the number of people exposed (ppl); and **throughput** in terms of aircraft arrivals per hour (AC/hr) or total aircraft per day (AC). This leads to a six-dimensional tradeoff hyperspace to be considered in the case study. Two metrics are used to quantify population noise exposure, the Day-Night Average Level (DNL) and Time-Above 60 dB (TA60dB), both on the A-weighted scale. The former metric logarithmically averages aircraft noise over the course of a day at a given location on the ground whereas the latter metric quantifies the total amount of time a given location (or population) is exposed to 60+ dB of aircraft noise per day. For the time-above metric, the 60 dB(A) threshold was chosen because this is the minimum noise level likely to interfere with normal conversation [107].

Figure 7-3. Stakeholder and System Output Matrix (Case Study 2).

99

Given the six previously mentioned systems outputs, the distribution of benefits and costs amongst these three stakeholders of interest is shown in Figure 7-3. In Figure 7-3, the direct and indirect benefits and costs are shown, however, for the analyses performed in this case study, only the direct costs and benefits for each stakeholder are quantified. As seen in Figure 7-3, the airport stakeholder derives a direct benefit from aircraft landing at the airport, but airports also have to deal with the cost of exposing communities to aircraft noise, despite the fact that they do not directly cause aircraft noise. The airline incurs the costs associated with operating aircraft such as flight time and fuel burn. However, the airline also benefits from aircraft throughput, specifically through carrying passengers and the ensuing revenue created. Lastly, the only direct impact to the community is noise exposure and they therefore do not receive any direct benefit from the operation of aircraft. In order to simplify the valuation aspect of this case study, all stakeholders are assumed to bear the cost of emissions indirectly since these emissions are effectively disseminated into the global atmosphere when operating aircraft.

As can be seen by the distribution of costs and benefits (system outputs) in Figure 7-3, there are instances of stakeholder alignment and noticeable stakeholder misalignment. The airline and airport stakeholders are roughly aligned since they both benefit from throughput but bear the cost of noise, so the only difference between the two is that the airline incurs costs from sources other than noise, namely, the cost of fuel and time. However, stakeholder misalignment arises because the community does not receive a direct benefit from the operation of aircraft and instead only bears the cost of noise, which means that the community stakeholder will likely emphasize a stronger preference for noise reduction than the airline and airport stakeholders. This misalignment will be explored in more detail in the ensuing case study analyses.

7.3.3. Valuation

Amongst the potential valuation methods mentioned in Section 4.3.2, there are many viable options for valuing the costs and benefits (impacts) of aircraft approach procedures. However, in this case study, it is assumed that value is a uniform-additive function of cost and benefit, so the CBA approach discussed in Section 4.3.2 is used. Since in this case study the time scale associated with the system output quantifications for a given approach procedure is small (*i.e.,* on the order of minutes), discounting is negligible and the value function in this case study simplifies to:

Equation 9

$$Value = \sum_{\forall i}\left(\lambda_i \cdot Y_i\right)$$

In Equation 9, *Value* is the benefit of a system less it respective cost. $Y_{i,}(t)$ is the ith system output and $\lambda_{i,}$ is the ith uniform preference weighting corresponding to the ith system output, respectively. If λ_i is negative and positive, then the ith system output is a cost and benefit, respectively – thus, *Value* is benefit minus cost. The set of *Y's* are the system outputs in Figure 7-3, and the set of $\lambda's$ are collectively referred to as the "λ-Set" and are the embodiment of the value/belief systems in Table 7-1. Thus, if a λ is a cost in Table 7-1, it is implicitly negative. The sign of *Value* in Equation 9 indicates the relative contribution of cost and benefit; if *Value* is positive, benefits contribute more to value than costs and the converse is true if *Value* is negative.

It is important to note that *all metrics are computed on a daily basis*, so metrics measured on a per aircraft basis are multiplied by the daily aircraft throughput.

PREFERENCE STRUCTURE

Each stakeholder has a "λ-Set" (*i.e.,* preference structure) that translates their respective costs (and benefits) into their value, given the uniform-additive, cost-benefit value function used in this case study. The stakeholder λ-Sets are defined in Table 7-1 along with reference values for each λ.

Cost of Fuel and Time		Cost of Noise			Benefit from Throughput	
Airline		Airport	Airline	Comm.	Airport	Airline
λ_{DOC}	λ_{Fuel}	$\lambda_{Noise, AP}$	$\lambda_{Noise, AL}$	$\lambda_{Noise, Com}$	$\lambda_{Thru, AP}$	$\lambda_{Thru, AL}$
Operating cost	Fuel cost	Noise Cost to Airport	Aircraft Noise Levy	Noise Cost to Comm.	Landing **charge**	Ticket **revenue**
-1164 $/hr	-2.49 $/gal	-41.10 $/ person	-0.41 $/ person-DNL	-6.00 $/ person-hr	0.00436 $/AC-lb	5100 $/AC

Operating cost of an A320 | Price of Jet-A Fuel | Unknown but best estimates are provided | Landing fee at BOS | Pro-rated ticket price

Table 7-1. Stakeholder λ-Sets (Case Study 2).

In Table 7-1, λ_{DOC} is the average hourly operating cost, less fuel, of an A320-200 (the aircraft considered in this case study) and λ_{Fuel} is the price of Jet-A fuel [78,79]. The throughput benefit to the airport, $\lambda_{Thru,AP}$ is assumed to be the current landing charge per aircraft at BOS, which is the airport of interest in this case study[2]. And the throughput benefit to the airline, $\lambda_{Thru,AL}$, is the revenue generated from ticket sales assuming a full passenger load and a ticket price pro-rated by the proportional distance of the approach leg to a trip from New York (JFK) to BOS, which is the assumed trip in the case study analyses. While this approach to quantifying the benefit of throughput is a direct, revenue-centric approach, future research is

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[2] Airport revenue generated from passengers while they are in the airport is not considered because this is outside the modeling scope of the case study.

needed to develop more appropriate metrics to capture the benefit of throughput in this case study. In particular, the airport and airline really care about minimizing departure delays, which can be mitigated with increased throughput. Thus, future work in determining the benefit of throughput should focus on relating throughput to the effect it has on an airline's ability to minimize passenger delays at airports and, for the airports, the resulting utility, or benefit they derive from maintaining passenger contentment, which directly relates to volume and length of delays within airports and thereby the aircraft throughput. Therefore, future work in defining the benefit of aircraft arrival throughput to airports and airlines should consider the aforementioned direct and indirect benefits to passengers.

The cost of noise for all three stakeholders requires slightly more explanation since these costs are dependent on several factors. As shown in Table 7-2, the cost of noise for the airport and airline is derived from DNL because for these stakeholders, current policies governing (and monetarily penalizing noise) are based on DNL. Conversely, the community noise cost basis is Time-above 60 dB (TA60dB) because

Airport	Airline	Community
Noise Metric		
DNL ≥ 65 dB	DNL ≥ 65 dB	Time-above 60 dB
Noise Cost Factors		
Noise pollution	Noise pollution	General annoyance
Soundproofing homes	Passenger ride quality	Night awakenings
Community exposure	Community exposure	Learning disruption
Airport noise policies	Airport noise policies	Building vibrations
Terminal noise quality		Health impacts
		Housing depreciation
Reference Values for λ_{Noise} (per day of operations)		
-41.10 \$/person	-0.41 \$/person-DNL	-0.06 \$/person-hr

Table 7–2. Cost of Noise Explanation.

they care about how much time per day they are annoyed by aircraft noise, which is not directly captured through DNL given its use of logarithmic noise averaging.

λ_{Noise} for the stakeholders is a complicated metric to determine as it depends on the important cost factors shown in Table 7-2. These cost factors should be considered when determining a given stakeholder's respective λ_{Noise} since they all influence the value of this multiplier. For example, the community cost of noise is measured by TA60dB and its value depends on the community's: general annoyance from aircraft noise, night awakenings due to noise, learning disruptions from noise, building vibrations from noise, health impacts from noise, and housing depreciation from noise. Given the various cost factors for each stakeholder, Table 7-2 provides some reasonable reference values for each stakeholder λ_{Noise}, recognizing

that there may be significant uncertainty in these values. The λ_{Noise} for the airport was estimated assuming that: (1) the only cost incurred to the airport from noise is the cost of soundproofing homes, which is estimated at \$35,000 per home; (2) the cost of soundproofing is only incurred when a household is exposed to 65+ DNL; (3) there is an average of 2.2 people per household; and (4) that airports amortize the cost of soundproofing homes on an annual basis. For the airline, λ_{Noise} is based on current noise levies at airports in Europe and Asia [108]; these levies are transformed to a person-DNL cost basis assuming a charge of \$0.41 per person-DNL exposed to DNL $\geq$ 65dB. Lastly, λ_{Noise} for the community is based on recommendations from the Aviation Environmental Portfolio Management (APMT) Tool regarding a person's willingness to pay to avoid being exposed to aircraft noise [109]. APMT estimates λ_{Noise} to be roughly 0.06 \$ per person-hour of exposure to 60+ dB of aircraft noise; therefore, the community stakeholder only incurs the cost of noise when a population is exposed to 60+dB of noise.

It is important to acknowledge that there may be uncertainty in some of the λ values for a given stakeholder in this case study. While best estimates were made for these values, an important consideration in this case study remains how uncertainty in the λ values affects the stakeholder value propositions.

7.3.4. Proposed System Changes

Since the system of interest in this case study is an operational procedure, the interpretation of change is different than in the first case study, namely, that sources of change are instantiations of innovation in this particular case study. Technology Change occurs through the use of GPS technology, which in turn enables the
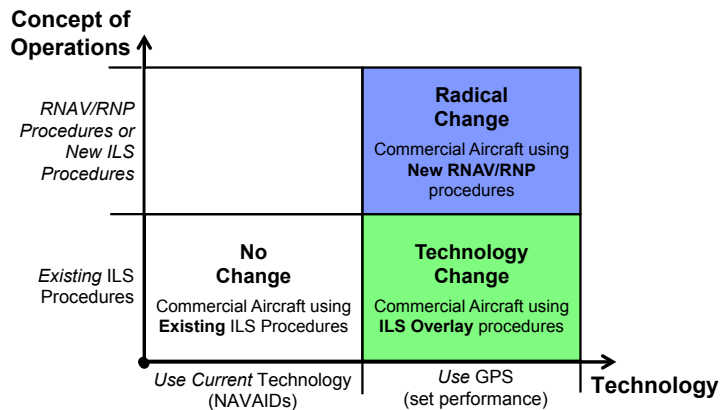
Figure 7-4. Change Taxonomy (Case Study 2).

development of new RNAV/RNP approaches (operations), which is a demonstration of Radical Change. Even though the performance of GPS may vary, in this case study either GPS is used in aircraft or not; hence, the Technology Change, or Innovation axis is binary.

In this case study, the two analyses that will be conducted compare an existing ILS route into a runway relative to a newly proposed RNAV/RNP route into the same runway. Instances of Technology change are

103

not considered because these lead to ILS Overlay procedures, which are ILS procedures except that they replace the use of NAVAIDs with periodic radio check-ins by pilots with ATC. Therefore, given the system outputs considered in this case study, the only change observed with these procedures relative to a given ILS procedure is the throughput along the ILS route via a reduction in the required separation distance between aircraft (*i.e.,* an increase traffic density) allowed by using RNAV/RNP. Therefore, the results of examining ILS Overlay procedure are already known, given the system outputs and assumptions made in this case study.

7.3.5. System and External Factor Models

The system model is called the Noise and Performance Impact Model (NPIM) and it will be described first followed by a discussion about the method used to compute population noise exposure.

NOISE AND PERFORMANCE IMPACT MODEL

The impact of approach procedures are modeled using a combination of the Integrated Noise Model (INM), which is an aircraft noise modeling software developed by the FAA[3], and a custom-built aircraft performance post-processor, which uses data from Piano-5, a professional aircraft modeling tool [82]. The various constituents of the NPIM are shown in Figure 7-5. The analyst's role in the NPIM is to propose changes by selecting an aircraft type and approach traffic volume (per day). The analyst then inputs an ILS or RNAV/RNP approach procedure for aircraft to follow. The two other required inputs for the NPIM are 2010 U.S. Census Data[4] and terrain data (topography) for the greater geographic area around the airport of interest. Given these inputs, INM is then used to compute the noise dispersion and approach flight path details, and these are then input to the post-processor. With the flight path details, the post-processor then computes the flight

Figure 7-5. Noise and Performance Impact Model.

performance, including fuel burn, flight time, and emissions, which are some of the system outputs of interest in this case study. The population noise exposure is computed using the noise dispersion data

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[3] Available online at http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/inm_model/ [retrieved December 13, 2011].
[4] Available at http://www.census.gov/geo/www/2010census/centerpop2010/tract/tractcenters.html.

104

output from INM and the 2010 U.S. Census Data[5] as described in the next paragraph. The outputs of the post-processor yield the system outputs and ultimately stakeholder value propositions in this case study. It is important to note that in this case study approach procedures are analyzed for *one day* of operations so all system outputs (impacts) correspond to 24 hrs of operations.

<u>POPULATION NOISE EXPOSURE</u>

The population noise exposure is computed by merging the noise contours output by INM with the 2010 US Census Tracts. The algorithm used is a nearest neighbor search, which finds the nearest census tract for each noise contour; this is conceptually represented in Figure 7-6. The noise contour discretization
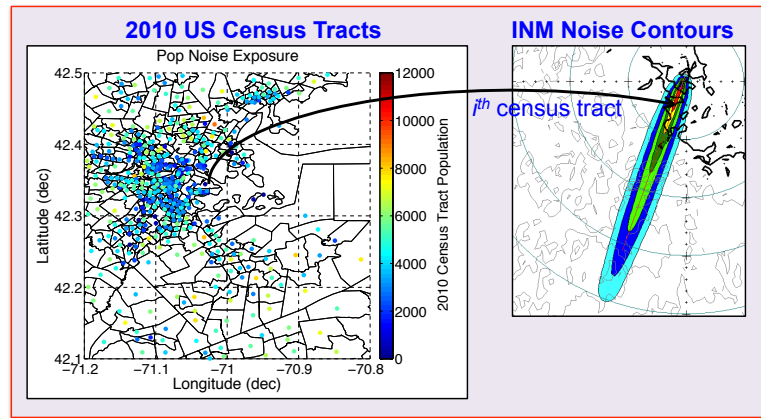
Figure 7-6. Computing Population Noise Exposure.

is 1 dB for the DNL metric and 1 hour for the Time-Above 60 dB metric.

7.3.6. Modeling Changes in Technology

The technology of interest in this case study is GPS and equipping aircraft with GPS represents innovation in aircraft design. Although GPS can have varying performance levels, in this case study, the Technology Change, or Innovation axis is binary in the sense that GPS is either used or not. Considering varying GPS performance levels entails evaluating the assurance of GPS precision and accuracy, which is beyond the scope of this research and case study. In reference to approach procedures, since the required separation distance between aircraft in terminal airspace is dependent on the location of the nearest radar, this varies by airport and so throughput changes (via the use of GPS) will vary by airport. Many airports have radar stations collocated with the airport at which point minimum allowable separation distance is around 3nm, which is the minimum allowable separation distance between aircraft without GPS equipage assumed in this case study.

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[5] The post-processor is used to quantify population noise exposure rather than INM because INM v7.0 cannot process 2010 U.S. Census data.

7.3.7. Modeling Changes in ConOps

Operational Changes are manifested through RNAV/RNP-modified ILS procedures, or completely new RNAV/RNP procedures. Existing ILS approach procedures are always considered the datum and the airport of interest specifies these[6]. RNAV/RNP-modified procedures are assumed to be ILS procedure overlays except that aircraft separation distance can be reduced via RNAV/RNP. Designing new RNAV/RNP approach procedures involves creating new ground tracks and the associated altitude, speed, and thrust versus ground track profiles to fully define a given procedure. Given the allowable degrees of freedom in RNAV/RNP procedures, RNAV/RNP ground tracks may be more geometrically complex than ILS approaches.

Since there are many degrees of freedom when designing new RNAV/RNP procedures, part of this case study development effort went towards developing a method for structuring the design of new RNAV/RNP routes. This method is a design of experiments (DoE) approach and its purpose is to hypothesize the RNAV/RNP route that best balances two criteria: the cost of the flight path parameters (*i.e.,* time and fuel) and critical (*i.e.,* 60+ dB) population noise exposure. The details of this method can be found in Appendix B. The suggested best route from this method is then fully analyzed with the NPIM described in Section 7.3.5. The motivation for using this front-end DoE method is that executing the NPIM takes 4-6 hours *per single* approach route analysis. Consequently, the cost of assessing a route is very expensive and the advantage of the DoE method is that it provides an educated guess as to the best route to invest in analyzing with the NPIM, which has proven a much better approach than randomly guessing a route based on the author's experience. The only limitation of the DoE method is that it selects the best route using surrogate models for the system outputs in this case study, so there is no guarantee that the route suggested by the DoE method will turn out to reflect its estimated system outputs when it is analyzed in detail with the NPIM.

7.4. Analyses

This section presents the case study analyses, which provide a different perspective of applying the framework in order to assess the impact of changes in aircraft systems than in the first case study. Before the specific analyses are presented, the background for the analyses and key assumptions are discussed. Two important notes to keep in mind are the sensitivity of the results to the assumptions mentioned hereafter and that all results are quantified for one day of operations (24 hours of arrivals).

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[6] Current ILS procedures at US airports can be found at <http://www.airnav.com/airport/>.

7.4.1. Background

The analyses in this case study look at altering commercial aircraft approach procedures into Boston-Logan (BOS) airport. The runway layout at BOS is shown in Figure 7-7 and at BOS, the majority of aircraft arrive from, and depart to, the southeast and west. Consequently, many arrivals using current ILS procedures pass over densely populated suburbs around Boston, or fly east of BOS into the Atlantic Ocean before beginning final descent in order to avoid populated areas. In either of these scenarios, assessing the impact of a given approach procedure (route) requires the consideration of the important tradeoff between noise exposure to local communities around Boston and flight performance (as measured by fuel burn and emissions), as these two impacts are often competing.
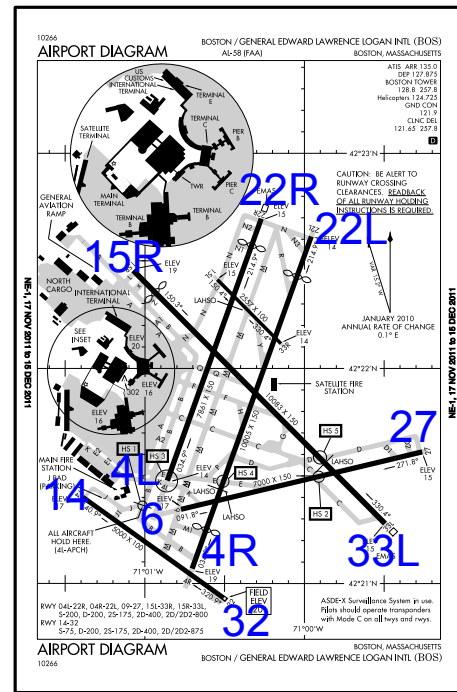
Figure 7-7. BOS Runway Configurations.

In this case study, aircraft approach procedures are considered to be approach operations at or below an altitude of 6,000 ft. Phases of approach operations include descending (either continuously in altitude or with discrete altitude plateaus), landing, and rollout. Existing approach procedures are ILS approaches whereas the RNAV/RNP procedures are referred to as RNAV approaches (for simplicity). As mentioned previously, the inherent tradeoffs for these procedures span multiple stakeholders including communities, due to changing geographic noise exposure with changing procedures, and airlines, due to changing operational costs with changing procedures.

7.4.2. Problem Scope and Assumptions

The major assumptions in the analyses are summarized hereafter. It is important to keep these assumptions in mind when interpreting the case study results and the ensuing discussion.

- An intentional simplification is that all air traffic consists of A320-200 aircraft

- The maximum single runway throughput is 18 aircraft arrivals/hr (432 arrivals/day)

- To provide an even comparison basis, all fights originate from a Providence, RI flyover at 10,000 ft

- Cruise before a given approach route begins at 10,000 ft and all aircraft fly the same descent profile thereafter based on distance from the runway of interest

- Local communities are aggregated and segregated by the 2010 U.S. Census Tract boundaries

- Noise attenuation due to terrain is not considered in the analyses[7].

- 3nm is the required length for the final stabilized portion of an approach

7.4.3. Overview of Analyses

Two analyses are performed in this case study, which collectively evaluate the No Change and Radical Change categories in the Change Taxonomy; thus, the Operational Change and Technology Change categories are not analyzed. Operational Change is not analyzed because it involves designing new ILS procedures, which is not of interest in this case study since Boston-Logan airport has already defined their allowable ILS approach procedures. And the Technology Change category is not analyzed because the system outputs will be identical for an ILS and RNAV/RNP-modified ILS route on a per flight/approach basis, with the possible exception of throughput, which may be higher on the RNAV/RNP-modified ILS route. Thus, this change category does not require extensive analyses to understand the impact of Technology Change as compared to No Change. The resulting analyses performed in this case study are therefore as follows:

1. Baseline Study: This analysis evaluates current ILS approaches into RWY 4R at BOS using existing commercial aircraft (1 assessment).

2. Radical Change Study: This analysis evaluates a new RNAV/RNP approach into RWY 4R at BOS using commercial aircraft equipped with GPS (1 assessment).

Therefore, two change studies will be performed in order to quantify the impact of change in aircraft approach procedures in this case study.

7.4.4. Analyses and Results

Given the system outputs summarized in Section 7.3.2, misalignment was identified amongst the three stakeholders considered in the case study. Thus, in order to design and analyze new RNAV/RNP approaches, this misalignment must be addressed to find an amenable approach route for all stakeholders. Subsequently, the DoE method described in Appendix B is used to potentially find such a route and this will be discussed first in this section. Following this discussion, the results from analyzing the two operational

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[7] Given the proximity of Boston to the Atlantic Ocean and hence generally consistent and low elevation, terrain was found not to be a driving factor in terms of population noise exposure in the preliminary case study analyses conducted by the author.

scenarios (*i.e.,* approaches) will be presented, that is, the current RWY 4R (ILS) and the new 4R (RNAV) route.

<u>DESIGNING NEW RNAV APPROACHES</u>

In this case study, the three stakeholders each have unique value functions and thereby each stakeholder demonstrates a preference for a different combination of system outputs, which increases the difficulty associated with designing a new stakeholder-wide valuable RNAV approach. In order to resolve this misalignment and design a new RNAV route, the approach used herein is to create a supra-objective function by finding a common source of alignment amongst the stakeholders in at least one system output (tradeoff) dimension and then relegating the remaining misaligned output dimensions as negotiable constraints. It should be noted that this approach is not necessarily generalizable to resolving stakeholder misalignment for every problem, but it serves as a constructive and creative example for future adaptations of this approach to achieve stakeholder alignment. The basis for this approach begins with the three stakeholder value functions in this case study, as summarized in Equation 10. The acronyms in Equation 10 are defined on pg. 21.

Equation 10

$$V_{airline} = \left[\lambda_{Thru,AL} \cdot Thru \right] - \left[\lambda_{fuel} \cdot FB + \lambda_{time} \cdot FT + \lambda_{Noise,AL} \cdot Pop_{DNL \geq 65dB} \right]$$
$$V_{airport} = \left[\lambda_{Thru,AP} \cdot Thru \right] - \left[\lambda_{Noise,AP} \cdot Pop_{DNL \geq 65dB} \right]$$
$$V_{community} = - \left[\lambda_{Noise,Com} \cdot Pop_{TA 60dB} \right]$$

As seen in Equation 10, there is common alignment amongst the stakeholders with respect to noise, namely, that they all bear the cost of noise and hence minimizing noise is valuable for all stakeholders[8]. Given the stakeholders and their respective preferences, the key to finding a new, amenable approach route into RWY 4R therefore begins with minimizing population noise exposure since the stakeholders are commonly aligned along this output dimension. Thus, minimizing noise will be treated as the common objective function in the Design of Experiment Method discussed in Appendix B, specifically within the Track Finder Program, and the remaining considerations are the other contributors to value found in the airline and airport value functions. In the analyses performed in this case study, throughput is held constant and it is also exogenous to the design of a given approach, so this aspect of value can be effectively negated in designing new approach routes. The remaining aspect of value to capture is therefore the cost of flight operations, which is borne by the airline and consists of the cost of fuel and time. Since these factors are

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[8] Even though the Airline and Airport use DNL65dB metric whereas the community uses the TA60dB metric, these are correlated and can conceptually be thought of as the same noise metric for the purposes of executing the DoE method described in Appendix B.

notable contributors to airline value, they need to be accounted for in the optimization formulation in order to balance the noise minimization with these adverse value (*i.e.,* cost) factors. This is done through setting the flight path costs as a constraint, which can be negotiated between the airline and community stakeholder. The resulting supra-objective optimization problem used to design a new RWY 4R (RNAV) route via the Track Finder Program is stated in Equation 11.

Equation 11

$$\max \quad V_{common} = Cost_{Noise}$$
$$s.t. \quad 0 \le C_{path} \le 1.1 \cdot C_{path}$$
$$where \quad C_{Ops} = -\left[\lambda_{fuel} \cdot FB + \lambda_{time} \cdot FT\right]$$

Equation 11 finds the route that minimizes noise, V_{common}, subject to a constraint that encapsulates the flight path cost, a major contributor to the airline's value. As shown in Equation 11, the flight path cost is constrained between 0 (*i.e.,* the utopia) and an allowable set increase in the flight path cost, relative to some datum cost. In the case study analyses, the flight path cost is not allowed to increase by more than 10% relative to the datum cost, which is assumed to be the flight path cost of the current RWY 4R (ILS) route.

This supra-objective optimization approach therefore exploits any alignment amongst stakeholders by setting the aligned sources of value as the optimization objective function and then handles the remaining unique contributors to stakeholder value as constraints, which can be negotiated amongst the stakeholders. Given the problem formulation in Equation 11, this approach can ultimately be implemented via the Design of Experiment method described in Appendix B where the flight path constraint is effectively Option A in Figure B-1 and then Track Finder Program performs the optimization using the surrogate models within the method. This approach therefore provides a potentially powerful mechanism for designing new routes while also accounting for conflicting value structures from multiple stakeholders.

RWY 4R (ILS) AND 4R (RNAV) ROUTES

The analyses in this case study compare the currently implemented 4R (ILS) approach with a new 4R (RNAV) approach, which attempts to provide more value to the airline, airport, and community stakeholders. The 4R (ILS) approach is predefined by BOS but the 4R (RNAV) route was designed using the aforementioned supra-objective optimization problem derived from identifying stakeholder misalignment. As mentioned previously, given the problem formulation in Equation 11, the Design of Experiment method described in Appendix B can be used to design the new 4R (RNAV) route. In order to limit the computational requirements (runtime) of the Design of Experiment method, the greater Boston

area was discretized into a roughly 5.5 nm grid on which new 4R (RNAV) ground tracks may be defined. The track finder program starts with an initial guess and, then, as the Track Finder Program progresses, it continually reduces the number of people in the critical noise exposure corridor, while never exceeding a 10% increase in flight path cost relative to that of the 4R (ILS) route. Observing the execution of the Track Finder Program can educate stakeholders about the geographic areas that are likely the most valuable to explore in terms of new approach routes into BOS. Given the 5.5 nm grid assumed for the Tack Finder Program in this analysis, 1,274 RNAV approach routes met the flight path cost constraint. These viable approach routes are shown in Figure 7-8, which shows the population in the critical noise corridor versus the ground track distance and resulting flight path cost (by the color shading).
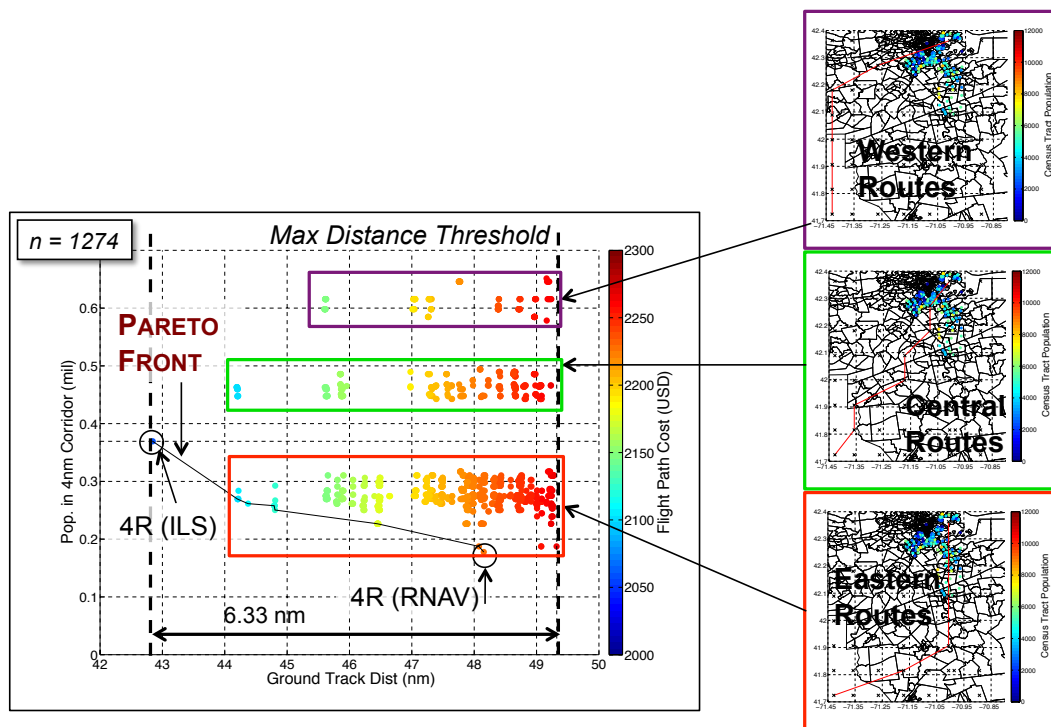
Figure 7-8. Track Finder Program: Resulting Tradespace.

As seen in Figure 7-8, there are three distinct potential route categories: western, central, and eastern. The western and eastern routes expose the highest and lowest number of people to noise, respectively, whereas the central routes fall somewhere in between the western and eastern routes. These observations tell much about the potential for new routes into BOS from the west, south, and east, namely, that the western region of Boston is more densely populated and thus designing stakeholder-amenable routes in this region will be much more difficult than doing so in the east where the population is less dense. This therefore suggests more promise on the aggregate in utilizing the Atlantic Ocean and the greater southeastern and eastern area of Boston to design new approach routes. Interestingly, the currently implemented 4R (ILS)

111

route, which is highlighted in Figure 7-8, is between the eastern and central route groups and its respective flight path cost is the lowest since it roughly follows the great circle from Providence, RI to BOS. However, the disadvantage of this route is that it exposes about 364,000 people to critical noise, so it is suboptimal with respect to that objective. This incentives the design and analysis of a new 4R (RNAV) route, the results of which are discussed in the next section.

SYSTEM OUTPUTS

The 4R (RNAV) route analyzed herein is indicated in Figure 7-8 as "4R (RNAV)." This 4R (RNAV) route was chosen because it leads to the least population in the critical noise corridor and meets the constraint of no more than a 10% increase in flight path cost; however, given the tradespace in Figure 7-8, it is important to recognize that there may be more preferable RNAV routes that have slightly less cost with slightly more population exposure, depending on the stakeholders; these are likely to fall on the Pareto Front shown in Figure 7-8 by the light black line, where the utopia is at the origin of the plot. The ground tracks corresponding to the 4R ILS and RNAV routes are shown in Figure 7-9. As seen in Figure 7-9, the currently used 4R (ILS) route takes the shortest path into BOS
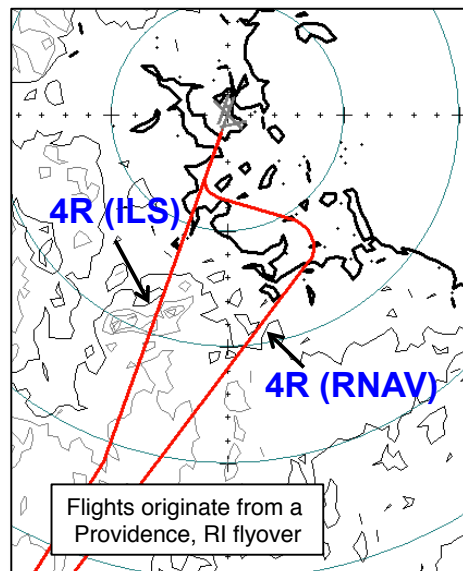
Figure 7-9. RWY 4R (ILS) and 4R (RNAV) Approach Routes.

from Providence while staying east of South Boston, which is heavily populated and right below the airport. The new 4R (RNAV) is a bit longer and more indirect than the ILS route but exploits the lesser populated areas east of BOS and completes its final approach by flying through the Boston harbor.

These two routes demonstrate two types of change, or innovation in the Change Taxonomy: 4R (ILS) "No Change" and 4R (RNAV) "Radical Change." Before the value proposition summary for these two routes is given, the system output comparison between the routes is explored. The first system output comparisons are DNL65dB, for the airline and airport stakeholders, and TA60dB, for the community. The DNL65dB comparison is shown in Figure 7-10. In Figure 7-10, DNL is constrained to 45+ dB and the critical threshold, in terms of adversely affecting the airline and airport stakeholder value, is 65 dB. As can be seen in Figure 7-10, neither approach exposes a population to a DNL of 65dB or greater. In the right of the figure, the corresponding DNL contours are shown for the two routes analyzed.

112

Population Noise Exposure-DNL Profile (DNL ≥ 45)
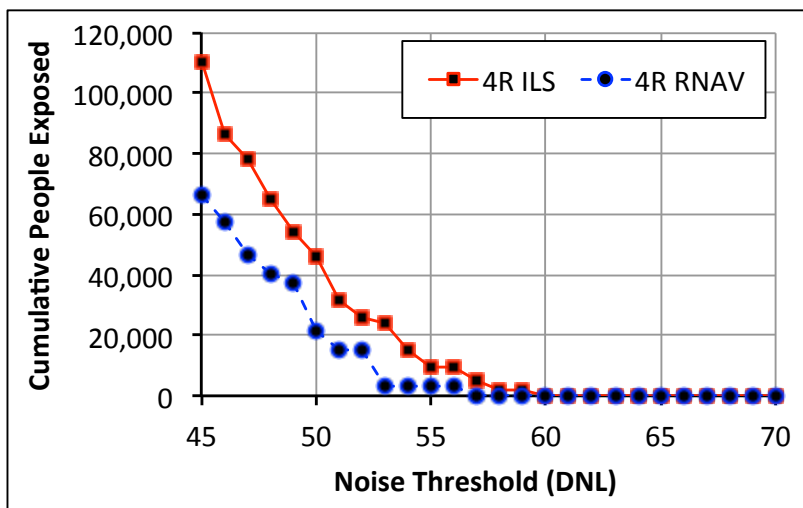
DNL Contours
(DNL ≥ 45)
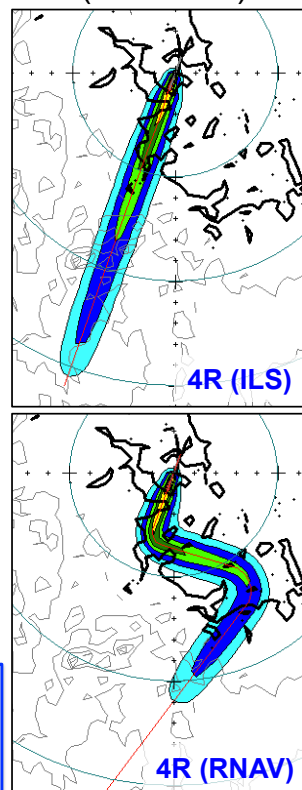
Figure 7-10. Noise Comparison (DNL).

The corresponding noise results for the community, as quantified by the TA60dB metric, are shown in Figure 7-11. As can be seen in Figure 7-11, there is a relatively consistent 136,000-person reduction in the population exposed with the 4R (RNAV) route along the x-axis in the figure, which suggests that the
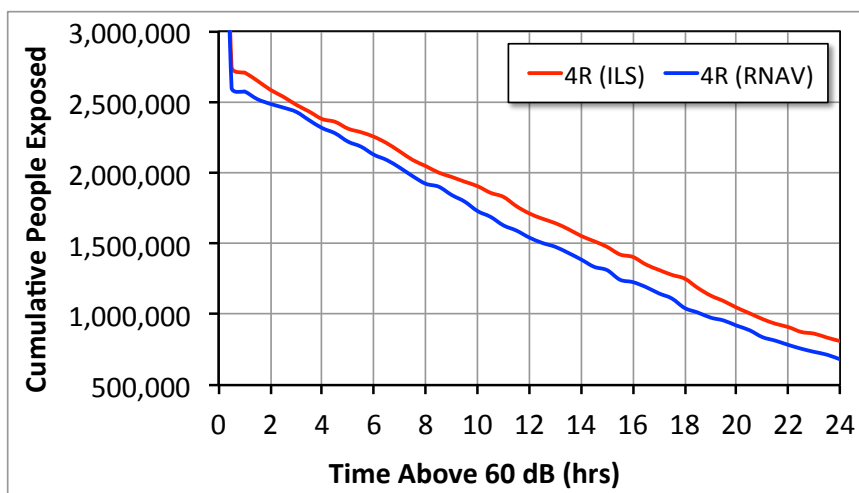
Figure 7-11. Noise Comparison (Time-Above 60 dB).

113

4R (ILS) route is fairly suboptimal in terms of minimizing population noise exposure. Specifically, the population exposed to 30+ minutes of 60+ dB per day is less by 146,194 people, or 5.3% with the 4R (RNAV) route as compared to the 4R (ILS) route.

The resulting comparison of the system outputs corresponding to the two RWY 4R routes analyzed in this case study is shown in Figure 7-12. Note that these results are for one day of operations (arrivals), which is 18 aircraft arrivals/hr or 432 total arrivals in a day. In Figure 7-12, the difference in system outputs between the RNAV and ILS routes (*i.e.,*
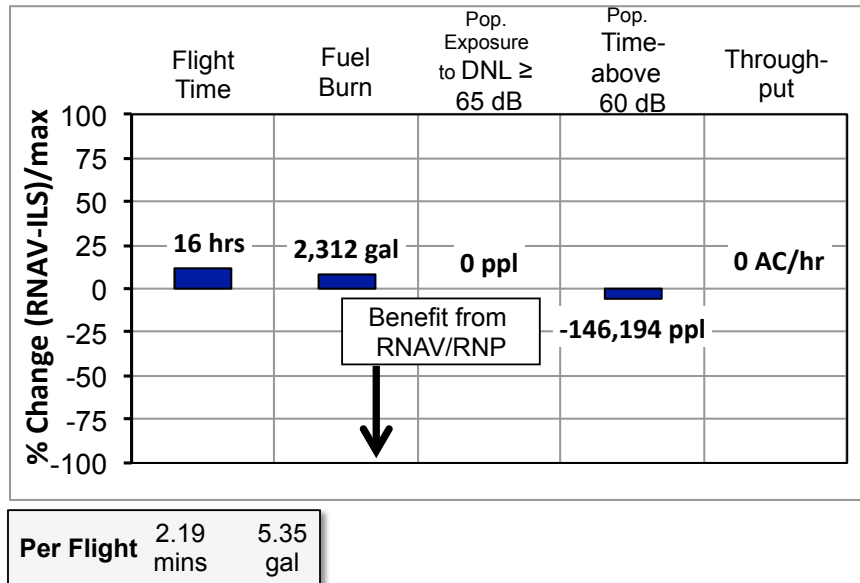
Figure 7-12. System Output Comparison.

RNAV – ILS) are shown, so, in the figure, benefits from the RNAV route are indicated as negative changes or reductions. As seen in Figure 7-12, there is no change in the DNL exposure at 65+dB, however, there is a reduction in the Time-Above 60 dB noise metric as previously substantiated. The tradeoff for this reduction is an increase in the flight path parameters, which is indicated in Figure 7-12 on the aggregate, or on a per flight basis in the lower left of the figure. The question for the airline stakeholder thus becomes does the reduction in noise offset the increase in flight path cost? This tradeoff can be interpreted in a variety of ways, for example, 66,755 less people are exposed to noise above 60dB for 30+ minutes during the day, for each 1min increase in flight time, per aircraft arrival. Ultimately, the system output tradeoffs are best captured through the value propositions for each stakeholder, which are summarized in Figure 7-13.

114

The value proposition results in this case study are summarized in Figure 7-13. Given the value results in Figure 7-13, the airline value is observed to decrease with the 4R (RNAV) route by $25,133 (-1.3%) because of the flight path cost increase associated with this route (recall that 65+dB of DNL exposure did not change).
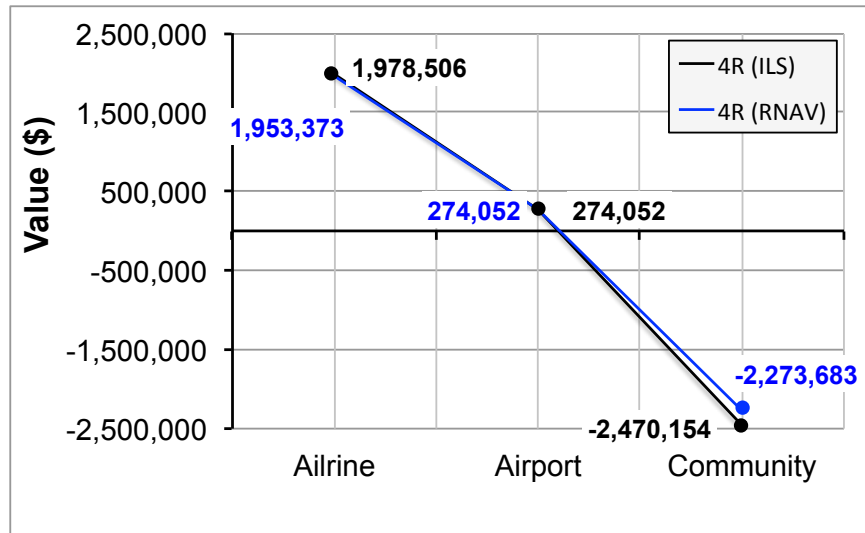
Figure 7-13. Value Propositions (Case Study 2).

The airport value remains positive and unchanged simply because throughput and 65+dB of DNL exposure does not differ between the two routes. And lastly, the community value remains negative but increases by $196,471 (+8%) due to appreciably less people exposed to 60+ dB for a 30 minutes or more during a given day with the new 4R (RNAV) route; this brings the community value with the 4R (RNAV) route closer to the theoretical maximum, or best community value of $0. The summary of the stakeholder value propositions in Figure 7-13 thus validates the approach used to design the new 4R (RNAV) route described in Appendix B, which, recall, minimized population noise exposure at the cost of increased the flight path distance (and cost). While the community assuredly benefits from the 4R (RNAV) route, given the severe competition in the current air travel market, the corresponding drop in value for the airline with this new route may be enough to combat the community's desire to use this route over the 4R (ILS) route, although they still maintain positive absolute value with the 4R (RNAV) route.

7.5. Discussion

The objective of the second case study was to evaluate the impact of changes in commercial aircraft approach procedures (operations). In this case study, Operational Change is manifested through alterations in approach procedures (ConOps) whereas Technology Change is manifested through GPS technology, which increases aircraft situational awareness. Three stakeholders were of interest in this case study: airlines, airports, and communities. The airline's value is derived from the operation of aircraft as well as any population noise exposure created from the aircraft. The airports value is similarly derived from

population noise exposure but also the arrival (throughput) of aircraft. Lastly, the community stakeholder provides a polarizing perspective of value in this case study since they only bear the cost of aircraft noise and do not directly benefit from their operation.

This case study yielded specific insights regarding the impact of change, or innovation in commercial aircraft approach procedures, which will be discussed first followed by a discussion of the unique implementation insights gained from applying the Tradeoff Analysis Framework in this case study.

7.5.1. Case Study Insights

This section presents the formal insights gained about the impact of changing aircraft approach procedures gained through applying the framework in this case study. The section begins with a discussion of the trends observed in the system outputs and value propositions and then discusses insights gained in this case study with regard to dealing with a large number stakeholders and uncertainty in the framework.

SYSTEM OUTPUTS AND VALUE PROPOSITIONS

The motivation for this case study was to examine the impact of changes in aircraft approach procedures at BOS (Boston-Logan Airport), where change is manifested through the use of GPS technology and new approach procedures (ConOps). This case study yielded important insights regarding the impact of innovative approaches into airports, specifically for RWY 4R at BOS, which was the runway of interest in the case study analyses. The resulting two types of change, or innovation analyzed in the case study are No Change and Radical Change, manifested by the current RWY 4R (ILS) route and newly designed RWY 4R (RNAV) route (see Figure 7-9), respectively. In terms of system outputs, as was the case in the first case study, the environment- and performance-related system outputs were at competition with one another. In particular, population noise exposure was a key "environmental" attribute in this case study and this system output competed with the performance-based outputs considered such as flight time. This made the process of designing new, stakeholder-amenable approaches very challenging due to the need to balance population noise exposure with the aircraft cost and performance.

Despite the aforementioned tradeoffs, using Tradeoff Analysis Framework and the specific methods within this framework applied in this case study, the value propositions for all three stakeholders corresponding the present (*i.e.,* 4R ILS) and new (*i.e.,* 4R RNAV) approaches into BOS were suggestive that an amenable approach can be found amongst these stakeholders. As summarized in Figure 7-13, the value results

116

specifically show an increase in community value (+8%) with a reduction in airline value (-1.3%) when using the newly proposed 4R (RNAV) approach due to its slightly longer length. Conversely, the airport value proposition did not change due a lack of DNL change at critical levels and no change in throughput with either of the 4R approach routes. Thus, while the 4R (RNAV) route examined seems like an amenable solution between the community, airline, and airport stakeholders, the current market for air travel is so competitive that even a small loss in value may be unacceptable to an airline. However, it is possible that with a little less compromise on airline flight path costs (*i.e.,* the cost of fuel, time, and emissions), a new 4R (RNAV) route can be found that yields an increase in value for both the community and airline stakeholders; this is discussed in more detail on reflection of the approach route used to design the 4R (RNAV) route in Section 7.5.2.

The value proposition results from this case study thus allow us to gain some insights about the type and magnitude of change, or innovation evaluated in this case study. First, in an absolute sense, innovation can be of valuable for all the stakeholders considered in this case study. Despite the loss in value by the airline due to the new 4R (RNAV) route, their value remains positive, and furthermore, the airport and community stakeholders see no change and an increase in value, respectively. This implies that the 4R (RNAV) route analyzed in this case study is not detrimental to maintaining positive stakeholder value. The issue, of course, is the small loss in value to the airline and the question of whether this offsets the notable increase in value for the community. Unfortunately, without real airline and community stakeholder's "in-the-loop" in this case study, this cannot be determined. However, the change in value observed for these two stakeholders due to the new 4R (RNAV) route offers promising hope that this route may be an amenable starting solution for these stakeholders to find an acceptable approach route into RWY 4R at BOS.

In summary of the key insights gained in this case study, analyzing the impact of change, or innovation for approach procedures has demonstrated that there are persistent tradeoffs associated with changing operations, which conforms to the findings in the other two case studies used in this research. This does not make innovation consistently desirable or undesirable, but the results of this case study instead do suggest that "win-win-win" situations can be found amongst the airline, airport, and community stakeholders with new RNAV/RNP approaches. However, since this case study did not design RNAV/RNP procedures following the Terminal Instrument Procedures (TERPS) criteria, a truly holistic picture of the benefits and

117

costs associated with innovation in aircraft approach procedures cannot be derived from these specific case study results[9]. Despite this, the current effort exhibited by the FAA to develop and implement RNAV/RNP procedures at airports across the country is evidence of their keen interest in discovering and exploiting the benefits of these procedures[10].

CHALLENGES INTRODUCED WHEN CONSIDERING A LARGE NUMBER OF STAKEHOLDERS

Another insight gained in this case study is that aircraft approach procedures inherently involve multiple stakeholders, who are likely to be misaligned in some capacity, in particular because the community stakeholder always incurs the cost of noise but receives no direct benefit from the operation of aircraft. Aligning these stakeholders may prove difficult, even more so when avoiding the simplifying assumption made in this case study that the community is one stakeholder, where in reality, each locale within the community/population of interest may have their own preferences as to avoiding aircraft noise and thus needs to be considered as an independent stakeholder. Consequently, if there are a large number of stakeholders of interest, this gives rise to additional issues such identifying stakeholder misalignment, facilitating such alignment, and visualizing the stakeholder value propositions, among other potential new issues introduced in the framework. Despite this, if local communities within a given population each have different preferences for avoiding aircraft noise, they may still be aligned since they all incur the cost of noise, but this ultimately depends on how sensitive their preferences are to the value (cost) of noise. This and other considerations such as representing numerous stakeholder value propositions are rich areas in terms of developing and evaluating the future applicability of the framework.

ADDRESSING UNCERTAINTY IN THE FRAMEWORK

It is also important to recognize that the insights gained in this case study are dependent on any potential uncertainty in the preference structure used to quantify the tradeoffs (see Section 7.3.3). While best estimates were made for all stakeholder preference structures (*i.e.,* λ-Sets), there is uncertainty in the λ for the emissions and, especially, the noise. Therefore, before generalizing the results and the ensuing insights gained from this case study, it may be important to account for this uncertainty in the case study results. In particular, it may be useful to quantify the sensitivity of the uncertain λ-Set values in relation to the space of proposed changes and thereby the system output and value space. Exploring this is left as recommended future work for this case study.

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[9] The purpose of TERPS is to prescribe the criteria for approach or departure route formulation, review, and approval in the United States.
[10] http://www.faa.gov/news/fact_sheets/news_story.cfm?newsid=8768

118

7.5.2. Framework Implementation Insights

This section discusses the insights gained about the Tradeoff Analysis Framework execution through applying the framework in this case study to assess the impact of changing aircraft cruise operations.

Given the multi-stakeholder considerations in this case study, the Tradeoff Analysis Framework was used to identify stakeholder misalignment and then subsequently facilitate alignment. The goal of facilitating alignment was to find an approach route into BOS that was satisfactory for all stakeholders. These two activities led to interesting framework implementation insights, which are discussed hereafter.

IDENTIFYING STAKEHOLDER MISALIGNMENT

Identifying misalignment can be done with the Tradeoff Analysis Framework, specifically using the preference structures from the valuation component of the framework. In using preference structures to identify stakeholder misalignment, it is important to recognize that misalignment ultimately depends on the sensitivity of value to the preference structure. If value is relatively insensitive to the preference structure, then alignment may be achieved through preferences having the same direction/sign (or form), depending on the valuation method used. Alternatively, if value is very sensitive to the preference structure, then even preferences of the same direction/sign (or form) may exhibit misalignment in terms of value. A resulting key aspect of this case study was using the framework to identify stakeholder misalignment. Specifically, in this case study, all the stakeholders considered in the case study incurred the cost of noise, thus having alignment with respect to this direction. However, the flight path parameters such as fuel burn and flight time did not directly impact the community or the airport, thus they were misaligned relative to the airline stakeholder who cared about these parameters since it affects their value. While the conceptual comparison of preference structures can isolate misalignment, analytical methods such as Principal Component Analysis may also be useful for identifying the underlying sources of misalignment amongst the stakeholders, as is demonstrated in the aircraft cruise operations and remote sensing spacecraft case studies (see Section 6.4.2 and 8.4.4), and as discussed in Section 9.1.3.

FACILITATING STAKEHOLDER ALIGNMENT

After identifying stakeholder misalignment with the Tradeoff Analysis Framework, the remaining step to be performed is to attempt to facilitate stakeholder alignment. This is perhaps one of the richest areas for the future framework development and application as there are numerous approaches for facilitating such alignment. Several options are discussed in Section 4.3.4 that may help achieve full alignment, or at least

119

partial alignment, through identifying dimensions of common alignment amongst stakeholders, if any, given the system outputs of interest. The methods listed in that section should be treated as complements as was the case when some of them were applied in this case study in order to facilitate stakeholder alignment.

Specifically, in this case study, a unique approach for facilitating stakeholder alignment was used, which relied on creating a supra-optimization problem that avoided the pitfall of weighting stakeholder value functions by their relative importance or "voting power," which often does not resonate well with stakeholders since this requires that they be openly ranked in importance relative to one another. This approach instead exploited the only source of alignment amongst the stakeholders, namely, reducing population noise exposure, and then isolated the misaligned aspects of value and left them as constraints to be negotiated. The result of this was an optimization problem to minimize population noise exposure (*i.e.,* the aligned direction) subject to the remaining misaligned elements of stakeholder value, which were formulated as separate constraints. This approach for facilitating stakeholder alignment required an implementation change to the framework in this case study, namely, to use it as a Design of Experiment platform (see Appendix B), which in turn relied on using the surrogate models described in Appendix B in place of the detailed NPIM discussed in Section 7.3.5 to optimize the design of new approach routes. The Track Finder Program within the Design of Experiment method essentially implements the Framework with Optimization in order to optimize an approach route, given the supra-objective problem formulation summarized in Equation 11, where the system transform is made up of the surrogate models. It was necessary to use the surrogate models for the initial RNAV approach route exploration since the detailed system model can take up to 6 hours to setup one potential route, analyze it, and prepare the results. Specific to this case study, the results of executing this DoE approach ultimately led to the successful design of a new 4R (RNAV) route that minimized population noise exposure while not appreciably affecting the airline and airport value propositions in an adverse manner.

In summary, given competing stakeholder preferences, it is likely that stakeholders are going to be reluctant to compromise their own value for the sake of improving another stakeholder's value, and this is only exacerbated in large system development programs having stakeholders from several different organizations. Thus, methods that facilitate alignment should err on the conservative side in achieving alignment, starting by finding smaller sources of alignment amongst the stakeholders, rather than trying to find complete alignment from the start, which may never exist anyway. Small sources of alignment

amongst stakeholders can go a long way in terms of building a rapport amongst stakeholders for future negotiations. Arrow's classic but still valid "General Possibility Theory," in part, concludes the lack of existence of a social welfare function that effectively resolves competing stakeholder preferences [63]. Despite this, much can be done in terms of achieving stakeholder alignment by using methods to identify and exploit partial alignment, which was exemplified in this case study.

COMPLEMENTARY FRAMEWORK USAGES

While the implementation of the Design of Experiment method (refer to Appendix B) in this case study via the Framework with Optimization does not seem novel, it demonstrates a complementary usage of framework versions and adaptations for assessing tradeoff hyperspaces. In this case study, the Framework with Optimization, with a simpler system model was used to determine the proposed change to be later analyzed in detail using the Framework with Multiple Stakeholders. A key takeaway from the framework implementation changes in this case study is therefore that evaluating the impact of innovation (changes) in aerospace systems may be best achieved through the complementary use of frameworks with different purposes, and they should therefore not be treated in isolation. In fact, considering the breadth and depth of potential applications of the Tradeoff Analysis Framework, the complementary usage of framework versions for analyzing a system may be more prevalent than not. This therefore demonstrates that unique usages of the Tradeoff Analysis Framework are likely going to be made in order to meet the objectives of a specific study using the framework, which is acceptable provided the underlying functionality of the framework is not altered (guidance for modifications to the Baseline Framework are discussed in more detail in Section 8.5.2).

SUMMARY

A lack of multi-stakeholder consensus is an issue prevalent in almost every field, and although the Tradeoff Analysis Framework may be used to develop and apply methods for achieving such consensus, there are a multitude of other suggested methods and approaches for achieving this[11]. Given the numerous options for facilitating multi-stakeholder consensus, it is easy to get lost in this area without having progressed much at all in the context of the larger problem to be solved. So in the context of this research and subsequent framework, addressing stakeholder misalignment remains relevant and important, but the caution offered is

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[11] The decision analysis domain mentioned in the literature review provides many of these methods, some of which are mentioned in Section 4.3.4.

that resources invested in achieving stakeholder alignment should balance the overall objectives of the framework implementation, thereby not overly biasing the framework development. Ultimately, this does not negate the usefulness of investing resources in resolving stakeholder misalignment, but it is better to take small steps towards developing a solution to this problem before expending a large, and perhaps blinded effort to do so.

8. CASE STUDY 3 – MULTI-STAKEHOLDER, REMOTE SENSING SPACE MISSION

The third case study applies the Tradeoff Analysis Framework to analyzing the impact of innovation for remote sensing space missions. The sources of innovation specifically arise from developing new technologies, which lead to the development of advanced spacecraft called fractionated spacecraft. In addition to advances in technology, this case study also considers advances in the replenishment strategies for spacecraft performing remote sensing missions. This case study is therefore the most complex in terms of the exploring the Change Taxonomy discussed in Section 4.2 since all four quadrants of the taxonomy will be explored. This section begins with a brief background on fractionated spacecraft and then follows with the application of the Tradeoff Analysis Framework in this case study.

8.1. Background

Fractionated spacecraft consist of physically independent structures, referred to as modules, where each module may not have the same subsystem/hardware composition as the other modules [110,111]. On-orbit, modules maintain a cluster or formation flying configuration and they wirelessly interact (collaborate) to share certain subsystem resources. Figure 8-1 conceptual depicts a fractionated spacecraft (Image source: Ref. [112]) with five collaborating modules. This collaboration differentiates fractionated spacecraft from constellations, although both are modular, and collaboration is a key area of technology development for fractionated spacecraft [111,113–115]. Through sharing resources, fractionated spacecraft can physically decouple the pointing-intensive mission payload(s) from subsystems not requiring such strict pointing by

Figure 8-1. A Fractionated Spacecraft Concept.

locating them on different modules. This ability to decouple subsystems and payloads may allow individual modules to be less massive and smaller than a comparable monolith, or yield other benefits extensible to a specific mission area [111,116,117]. In recent years, fractionated spacecraft have gained support because of their potential to offer improved lifecycle performance, or value relative to comparable monoliths. It is suggested that distributing system functionality amongst several collaborating modules can lead to better

123

"ility" (*e.g.,* survivability) performance while shortening development timelines and encouraging participation from non-traditional spacecraft manufacturers (via reducing barriers to entry) [116,118–121].

The focus of this case study is on remote sensing (earth imaging) spacecraft operating in the visible spectrum, and thus spacecraft considered here have an optical mirror system (*i.e.,* telescope) as their payload instrument. These spacecraft have an assumed orbit altitude and inclination of 700km and 98.1° respectively, a common altitude and inclination for remote sensing missions (consider GeoEye-1, Landsat-7, and EOS Aqua). In addition, a range of payload performance (*i.e.,* imaging resolution) is explored.

8.1.1. Sharing Subsystem Resources

The hardware required for sharing subsystem resources are relatively immature and may require substantial technology development (innovation) before they can be reliably used to field fractionated spacecraft [122,123]. These immature hardware components are referred to as enabling technologies. Past research conducted by the author on fractionated spacecraft has considered the employment of three classes of shared subsystem resources, and hence enabling technologies in fractionated spacecraft: (1) communication, computer system, and command & data handling (Comm_CS_C&DH) [119]; (2) attitude determination system and guidance navigation system (ADS_GNS) [124,125]; and (3) power generation and storage (Power) [111,126]. Given the current and near-term envisioned state of the art in space-qualified subsystem technologies, these three classes of shared resources are reasonable ones to consider for an analysis of fractionated spacecraft that could be operational in the near future. O'Neill and Weigel [127] provide a detailed assessment of the impact of these enabling technologies on fractionated spacecraft value.

8.2. Literature Review – Case Study 3

The fractionated spacecraft paradigm has gained support because of the potential it offers for improved lifecycle performance, relative to comparable monoliths. Distributing system functionality amongst several collaborating modules may lead to better performance in the "-ilities" (including adaptability, survivability and robustness), while potentially shortening development timelines and encouraging participation from non-traditional satellite manufacturers by reducing barriers to entry particularly in the defense context [116,118–121]. In order to assess the feasibility of the fractionated approach and validity of the above "-ility" related claims, the Defense Advanced Research Projects Agency (DARPA) System Future, Fast, Flexible, Fractionated, Free-Flying United by Information Exchange (F6) Program was initiated in 2007

[118,128][12]. During the intervening three years, under the broad programmatic umbrella of the System F6 program, a diverse set of conceptual fractionated spacecraft studies were undertaken [129–131]. Given the System F6 program's emphasis on *demonstrating benefits* in terms of lifecycle properties, studies have predominately sought to model system value under different types of lifecycle uncertainty [121,127,129–133]. The sources of uncertainty and their corresponding implementation in fractionated spacecraft models vary widely amongst these studies but they often relate to contingencies in launch vehicle reliability, funding, programmatic execution, on-orbit operation, market supply & demand, and national security (*e.g.,* protection against anti-satellite attacks). Therefore, despite the lack of method transparency conveyed in the System F6 program publications (due to proprietary concerns), it appears they considered typical risks in a spacecraft program. Aside from System F6 publications, Brown *et al.* [121,132] considered the contingencies of launch vehicle reliability, risk of in situ docking, and spacecraft (subsystem-based) reliability, whereas Dubos and Saleh [133] considered only spacecraft (subsystem-based) reliability. Lastly, O'Neill and Weigel [127] considered lifecycle contingencies resulting from launch vehicle reliability, programmatic issues (*i.e.,* schedule slips), spacecraft (subsystem) reliability, and human operator error.

Examined as a whole, the extant literature on fractionation has reached the consistent conclusion that when performance-equivalent fractionated and monolithic spacecraft are both subject to lifecycle risk (*e.g.,* on-orbit failure), fractionated spacecraft can yield less value-risk (*i.e.,* a narrower distribution of expected value) than comparable monoliths. O'Neill and Weigel identified a key source of the enhanced value of fractionated spacecraft relative to a comparable monolith to be the use of staged deployment, more specifically the ability to launch a set a smaller modules (as compared to the size and mass of a monolith) on one or more launch vehicles [127]. The importance of staged deployment in terms of dictating fractionated value lead to a demonstration of how potential mass (and size) savings of individual fractionated modules as compared to that of a monolith can be used to increase the mission (operational) lifetime of fractionated spacecraft, given certain launch vehicle accessibility constraints.

While the emphasis of fractionated studies in the literature is nominally on uncertainty, they fail to capture at least two important risks associated with the "flip-side" of fractionated value robustness opportunities, or arguments. First, while decoupling system functionality from a single physical location mitigates risk from a variety of failure modes, it also introduces several new and non-trivial sources of network risk resulting

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[12] Available online at http://www.darpa.mil/Our_Work/TTO/Programs/System_F6.aspx [retrieved October 5, 2011].

from the codependency of the modules. To this end, O'Neill and Weigel capture a preliminary exploration of these additional sources of risk created from sharing resources amongst modules (*i.e.,* failure-critical inter-module dependencies) and their implications for lifecycle value [127]. Second, it is important to recognize that the technologies required to enable the fractionated concept remain either relatively, or extremely immature from a space-qualified (or TRL) perspective [122,123]. While there is certainly value to exploring the *potential* for value robustness, one must not lose track of the very real technology risk/uncertainty associated with assuming that capability-enabling components for fractionated spacecraft will be ready in time, and at the performance level desired. This second category of risk has not been addressed in previous studies of fractionation.

This case study, will continue to contribute to the dialogue on assessing fractionated subject to lifecycle contingencies, but also extend beyond this by evaluating the impact of enabling technology and operational innovation on the potential value-risk offered by these spacecraft. While considering lifecycle contingencies remains important, this new holistic assessment of the risk and opportunities of fractionated spacecraft paints a more realistic picture for decision-makers interested in assessing when and whether to invest in the innovation required to support a fractionated future. Methodologically, this research and ensuing case study represents a first attempt to incorporate empirical insights to evaluate the impact of innovation on fractionated spacecraft system design operation, and ultimately their value propositions.

8.3. Application of the Framework

This section details the application of the Tradeoff Analysis Framework in this case study and begins with an overview of the framework followed by discussing each framework constituent in more detail.

8.3.1. Framework Application Overview

The application of the Tradeoff Analysis Framework in this case study is shown in Figure 8-2. As seen in the figure, the analyst inputs a type of change, or innovation to consider (*i.e.,* either technology, ConOps, both, or neither) and thereby the spacecraft architecture to be analyzed. The system architecture is assessed using the Spacecraft Evaluation Tool (SET), which is discussed in more detail in Section 8.3.5. Throughout a given time-window of interest, spacecraft modules may fail on-orbit. If so, they may be improved due to any subsequent innovation that has occurred since their last (re)build, therefore changing their respective performance and cost. The system outputs from the SET reflect these lifecycle characteristics and changes through an operational history of a spacecraft, including the system outputs of time-weighted average

performance (TWAP), time-of-service (ToS), stochastic lifecycle cost (SLCC), and Revenue, which are required to quantify the value proposition for the owner who is the stakeholder considered in this case study. The owner is specifically responsible for both developing and operating the spacecraft performing the remote sensing missions analyzed in this case study.
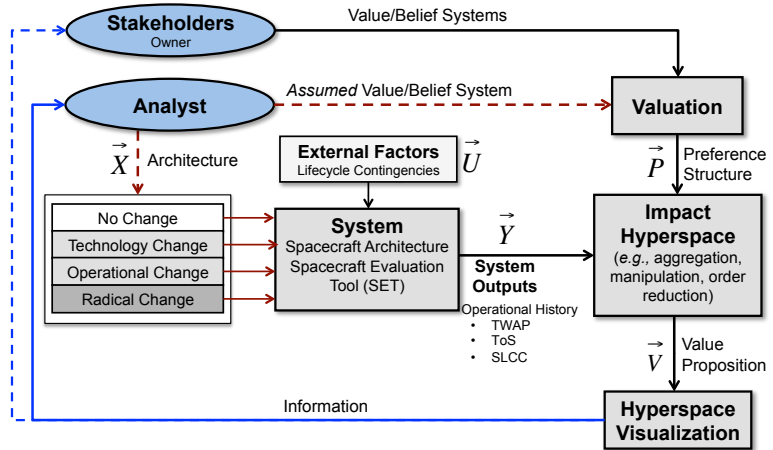
Figure 8-2. Framework Application (Case Study 3).

8.3.2. Stakeholders and System Outputs

In this case study, both the spacecraft developer and operator are important. The developer is responsible for researching, developing, manufacturing, and continuing to replace spacecraft (modules) on-orbit if they fail; it is important to note that the developer is not paid by the operator for the spacecraft produced. Conversely, the operator uses the spacecraft to perform a remote sensing mission and therein receives any direct benefits from that mission, which in this case study are images of the earth. Thus, the developer stands to take on the majority of the value, or financial risk since the only direct benefit they receive is through a successful flight demonstration, despite the fact that they bear the majority of the costs. On the contrary, the operator receives all of the direct benefits from operating a spacecraft such as the images of the earth generated, hence, the operator stands to incur much less financial risk than the developer.

The three system outputs of interest in this case study are shown in Figure 8-3 and they are **time-weighted average performance** (TWAP) in units of pixels-per-meter (ppm), **time-of-service** (ToS), in units of years (yrs), and **cost** (of development and operation) in units of Fiscal Year 2011 millions of dollars (FY11$M); the summation of the various sources of cost is called the Stochastic Lifecycle Cost (SLCC).

1. The first metric is the time-weighted average performance (TWAP), which characterizes the performance of a spacecraft relative to a particular time window (*e.g.,* the operational lifetime, program duration), balancing any performance with a potential loss or gain in said performance during the window. The formula for the TWAP metric is given in Equation 12.

127

Equation 12

$$TWAP = \frac{1}{T_w} \cdot \int_0^{T_w} R(t)\,dt$$

Here, TWAP (in ppm) and is the integral of spacecraft performance (resolution), R (in ppm), over the time window, T_w[13].

2. The second metric is time-of-service (ToS), which is the cumulative time of *active* payload service during the time window. Therefore, initial spacecraft development and subsequent rebuilding of payload module(s) do not contribute to the ToS.

3. Accompanying the spacecraft performance metrics is the stochastic life cycle cost (SLCC), which encapsulates the cost of developing, launching, and operating a spacecraft and, in addition, accrues the recurring and launch vehicle costs associated with replenishing spacecraft modules throughout the time window.

	Time-Weighted Average Performance (ppm)	Time-of-Service (years)	Development Cost (FY11$M	Operational Cost (FY11$M)
Developer			●	
Operator	●	●		●

Direct ● Cost   ● Benefit

Figure 8–3. Stakeholder and System Output Matrix (Case Study 3).

Given these system outputs, the disaggregation of benefits and costs given the developer and operator stakeholders is shown in Figure 8-3. This stakeholder situation is representative of the current proposal by the DARPA System F6 program for its first demonstration mission, namely, that a third party (*i.e.,* the developer) be responsible for manufacturing and deploying a fractionated spacecraft (or at least one of the required modules), and then another organization (such as the military) operates the spacecraft[14]. The goal of this stakeholder scenario is to demonstrate a key feature of fractionated spacecraft: the ability to easily integrate (simple payload) modules with an on-orbit infrastructure of modules; this is therefore essentially a "plug-and-play" architecture. The issue remains however, as substantiated in Figure 8-3, that the developer

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[13] Note: the time window does not necessarily equal the intended (expected) design lifetime of a spacecraft. For example, this would be the case when a mission or program length (*i.e.,* the time window) is larger than the feasible design life of spacecraft given maximum mass and size constraints imposed by the available launch vehicles.

[14] Available online at http://www.darpa.mil/Our_Work/TTO/Programs/System_F6.aspx [retrieved October 5, 2011].

does not receive the intrinsic benefits of the mission and bears most of the cost, whereas the opposite is true for the operator, recognizing that the cost of operations incurred by the operator is relatively small as compared to the developmental costs associated with spacecraft.

Given the aforementioned stakeholder misalignment and recognizing that the developer bears most of the financial risk, their incentive for participation is greatly diminished despite the apparent benefit to the operator. This case study therefore assumes a scenario representative of many spacecraft missions where the developer and the operator are the same stakeholder and thus they share in both the direct benefits and costs of the system; this entity will be referred to hereafter as the *owner* and they are responsible for manufacturing, deploying, operating, and replenishing spacecraft; this is the stakeholder reflected in the framework application in this case study (see Section 8.3.1).

8.3.3. Valuation

The valuation for the spacecraft owner in this case study depends on the three system outputs defined in the previous section. Since these system outputs can be all monetarily related, a net present value (NPV) approach is suitable for the owner valuation in this case study; an overview of the NPV method can be found in Ross *et al.* [52][15]. As a result, for the owner stakeholder in this case study, value is simply a function of revenue generated and cost, the former being derived hereafter.

Given that the spacecraft in this case study are remote sensing spacecraft, they may provide (sell) images to customers such as Google, who in turn use the images for their own financial gain (in Google's case, images for Google Maps). Therefore, in this case study, Revenue is proposed as a simple function of performance (resolution) over time, thus implicitly being dependent on TWAP and ToS[16]. The resulting revenue function is empirically derived from current image pricing policies from the European Aeronautic Defence and Space (EADS) Astrium and for GeoEye [134,135]. The ensuing revenue metric derived is a power function and given in Equation 13.

Equation 13

$$\text{Rev} = 46.28 \cdot T_w^{-0.626} \cdot \int_0^{T_w} \left(\frac{dTWAP}{dt} \right)^{-0.626} dt \quad \rightarrow \quad \text{Rev} = 46.28 \cdot \int_0^t R^{-0.626} dt$$

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[15] If other metrics like the "-ilities" such as flexibility and robustness were considered, which are not easily mapped to a cardinal scale such as monetary wealth, an alternative valuation method such as Utility Theory is likely more appropriate.

[16] Given Equation 12, resolution is the product of the rate of change of TWAP and the time window.

In Equation 13, R is the image resolution at time, t_i and revenue is quantified in FY11$M. Revenue is therefore generated over the time window during which a spacecraft operates, where the initial development and subsequent rebuilding of the payload modules does not contribute to revenue.

Figure 8-4 shows the revenue generated per year, assuming constant resolution as indicated by the x-axis in Figure 8-4. As seen in the figure, the current market for earth image acquisition is willing to pay appreciable amounts for marginal increases at high resolutions (*i.e.,* less than 1m). However, given the demand for increasingly higher resolution earth images, it has created a rapid decrease in the image revenue
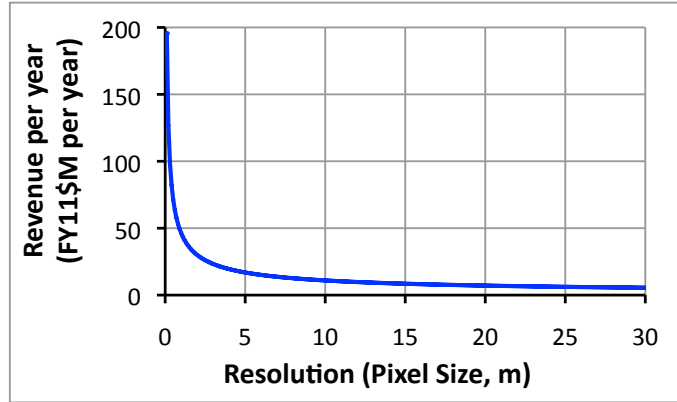
Figure 8-4. Spacecraft Revenue per Year.

generation as resolution decreases; thus, creating the asymptotic revenue limits observed in Figure 8-4. Given this revenue function, the resulting value proposition for the spacecraft owner is shown in Equation 14.

Equation 14

$$Value = \int_0^{T_w} (\text{Rev} - C) \cdot dt$$

Here, Rev is that shown in Equation 13, and C is the cost. Since both of these metrics vary in time, the value for the owner needs to be integrated over the time window. Accordingly, value is adjusted for inflation such that it is in FY11$M.

8.3.4. Proposed System Changes

In this case study, the analysis focus is on exploring the impact of technology and operational innovation for remote sensing missions, so the changes in the Change Taxonomy can be directly interpreted as characterizing types of innovation. Technology change, or innovation occurs through the development and subsequent performance improvement of the enabling technologies for fractionated spacecraft. The two enabling technologies considered are the Comm_CS_C&DH and ADS_GNS[17] shared resources. This case study is therefore unique to the previous two case studies in terms of the Change Taxonomy because change

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[17] The Power shared resource is not considered because the author's previous work demonstrated that, for a given performance level, sharing power amongst modules in a spacecraft is not cost or mass advantageous relative to a comparable monolith [111,136].

along the technology axis is continuous. While there are numerous facets to spacecraft operation including launch and in-situ operation, ConOps is considered to be the management of spacecraft replenishments over their lifecycle or the program duration considered. Given the multi-module composition of fractionated spacecraft coupled with the probabilistic nature of independent module failures, the operational dynamics of fractionated spacecraft are complex. Thus, ConOps innovation occurs through advances in module replenishment strategies over the time period of interest. The resulting four categories of change, or innovation explored in this case study are depicted in Figure 8-5 and as follows:
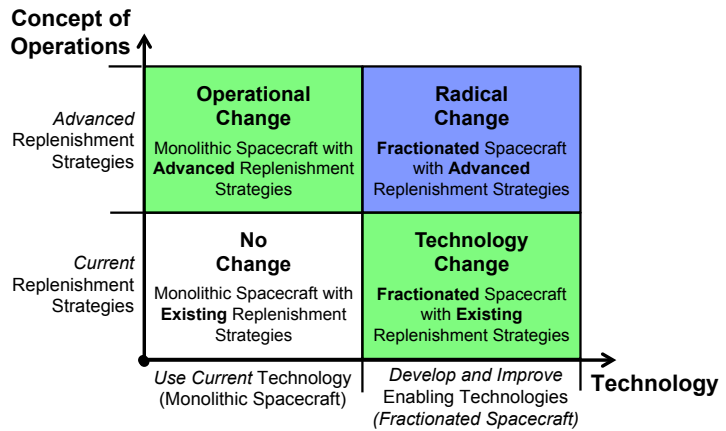
Figure 8-5. Change Taxonomy (Case Study 3).

- No Change: monolithic spacecraft using the datum (On-Demand) replenishment strategy.

- Technology Change: fractionated spacecraft that improve over time with advances in enabling technology performance using the datum (On-Demand) replenishment strategy.

- Operational Change: monolithic spacecraft using advanced replenishment strategies.

- Radical Change: fractionated spacecraft that improve over time with advances in enabling technology performance and that also use advanced replenishment strategies.

Therefore, only the monolith is assessed when evaluating the No Change paradigm, and for the remaining three change categories, one fractionated architecture will be analyzed[18].

8.3.5. System and External Factor Models

In this case study, the Spacecraft Evaluation Tool (SET) is used to assess monolithic and fractionated spacecraft. The functional divisions of the SET are shown in Figure 8-6 and each will be briefly described hereafter.

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[18] This architecture was one the most value-competitive fractionated architectures, relative to a comparable monolith, identified through the author's past research on fractionated spacecraft [127].

SET INPUTS

A given spacecraft assessment requires a set of inputs, and each of these inputs belongs to one of three groups: Launch Vehicle, Lifecycle & Design, or Spacecraft Architecture.

1. Launch Vehicle

The Launch Vehicle inputs specify candidate launch vehicles for initial spacecraft deployment and module

Figure 8-6. SET Functional Overview.

replenishments throughout a lifecycle. The current launch vehicle database consists of twenty-two launch vehicles from six different countries, but predominantly the United States. The vehicles span the small, medium, large, and heavy launch vehicle classes, which correspond to a mass to Low Earth Orbit (LEO) of <1000, 1000-3000, 3000-7000, and >7000, kg, respectively. The SET requires data pertaining to launch vehicle cost, stage masses and mass fractions, payload fairing dimensions, launch site latitude(s), and historical reliability; these data in the SET were obtained from launch vehicle manufacturers or the *International Reference Guide to Space Launch Systems* [137–140].

2. Lifecycle & Design

The Lifecycle & Design inputs define the mission context and certain parameters governing the design of a spacecraft. These inputs are grouped into eleven categories: orbital parameters, concept of operations, autonomy level, mission lifetime, sizing, payload performance, pointing requirements, stochastic lifecycle simulation, production, lifecycle uncertainties, and staged deployment; please refer to Ref. [111] for further discussion of these inputs.

3. Spacecraft Architecture

The Spacecraft Architecture inputs define the monolithic and fractionated spacecraft architectures to be assessed, and these inputs include the number of modules, and then for each module: the subsystem composition; the use of shared resources (*i.e.,* is the module a shared resource source or recipient, or neither); whether it has a mission payload; and whether it has a spacecraft-to-ground antenna. Each

132

spacecraft is built from the bottom up, that is, component-by-component, subsystem-by-subsystem, and module-by-module. If a module contains a mission payload it is referred to as a *payload* module, otherwise it is referred to as an *infrastructure* module; a monolithic spacecraft is considered a payload module. It is important to note that recipient modules will fail if the remaining (or only) source (infrastructure) module supporting it fails; this is referred to as an inter-module or dependent failure and is a unique source of risk for fractionated spacecraft (relative to monoliths since such linked failures cannot occur).

SET MODEL ALGORITHMS

A given spacecraft assessment is performed with three models: spacecraft, cost, and stochastic. These models and their respective high-level algorithms are shown in the Design Structure Matrix (DSM) in Table 8-1[19]. In a DSM, the X's in a given row represent the inputs required for the model algorithm on that respective row, whereas the X's in a given column represent outputs from the model algorithm in that respective column to other model algorithms.

Model		Algorithm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Inputs	1	SET Inputs	■															
Spacecraft	2	RSM Payload	X	■														
	3	Computer System, C&DH	X	X	■													
	4	Communication, TT&C	X		X	■												
	5	ADS, GNS	X				■											
	6	EPS	X					■			X							
	7	Propulsion, ACS, GCS	X					X	■			X	X					
	8	TCS	X	X	X	X	X	X	X	■			X					
	9	Power Required	X	X	X	X	X	X	X	X	■	X	X					
	10	Mass	X	X	X	X	X	X	X	X		■						
	11	Size, Volume	X	X	X	X	X	X	X	X		X	■					
Cost	12	LV Selection	X	X	X	X	X	X	X	X		X	X	■				
	13	COCOMO II	X	X											■			
	14	Parametric CERs	X	X	X	X	X	X	X	X		X				■		
Stochastic	15	Lifecycle Simulation (MCA)	X									X	X	X	X	X	■	
Outputs	16	SET Outputs		X	X	X	X	X	X	X	X	X	X	X	X	X	X	■

Table 8-1. SET Design Structure Matrix.

the model algorithm on that respective row, whereas the X's in a given column represent outputs from the model algorithm in that respective column to other model algorithms.

1. *Spacecraft Model*

The spacecraft model consists of the ten model algorithms shown in Table 8-1, each of which contains numerous smaller scope algorithms succinctly discussed in Ref [127]. The key output of these algorithms is the design of each spacecraft subsystem, characterized through metrics such as mass, dimensions (size), and power requirements.

2. *Cost Model*

The cost model quantifies the deterministic lifecycle cost (LCC) of a spacecraft. For a given set of modules, the launch vehicle selection model performs a full-factorial analysis of the candidate launch vehicles and selects one to three launch vehicle(s) that can collectively "fit" a spacecraft's modules, in terms of mass and

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[19] Notation: command & data handling (C&DH); telemetry, tracking, & control (TT&C); attitude determination and guidance navigation system (ADS, GNS); electric power system (EPS); attitude and guidance control system (ACS, GCS); and launch vehicle (LV).

size, given the destination orbit and launch site(s') latitude(s). The launch vehicle selection provides the option to use staged deployment strategies for launching fractionated spacecraft; refer to Ref. [141] for an example of staged deployment usage. The criteria for launch vehicle selection are to minimize and maximize the aggregate cost and reliability of launching a spacecraft respectively, replicating the behavior of a balanced cost and risk decision maker.

The remaining two algorithms in the cost model are the COCOMO II tool (for software only) and parametric cost estimating relationships (CER's). If possible, manufacturer quotes were obtained and used to cost subsystems, otherwise CER's are used. In total, the cost model employs thirty-one CER's characterizing a spacecraft's respective nonrecurring (NRE) and recurring (RE) costs. In terms of enabling technologies, the cost model only accounts for their respective hardware cost and assumes the cost of developing them is borne elsewhere.

3. Stochastic Model

The stochastic LCC encapsulates the cost of developing, launching, and operating a spacecraft and, in addition, accrues the RE and launch vehicle costs associated with replenishing spacecraft/modules throughout a lifecycle. The deterministic LCC does not account for the costs associated with replenishments and is thus the lower bound LCC of a given spacecraft.

The stochastic model quantifies the stochastic LCC of a spacecraft by simulating potential lifecycles for that spacecraft via a Monte Carlo Analysis (MCA). The model mimics a spacecraft's lifecycle such that relative to a given time in its respective lifecycle, future states of operation are not known with certainty. The stochastic model considers lifecycle contingencies belonging to four domains: launch, technical, operational, and programmatic [111,120,142]. The launch contingencies are a function of historical launch vehicle reliabilities, computed by Bayesian statistical probabilities. The technical contingencies are manifested in a probability distribution of failure times generated from the expected operational life of a given spacecraft module and its respective probability of infant mortality. (Probability of infant mortality is the probability a module will fail within its first year of on-orbit operation.) The operational contingencies are embodied in a time-dependent, Markov state space model of human error leading to spacecraft failure; the model allows for both normal and stressful-induced human errors and is based on historical NASA operator error [143–145]. Lastly, the programmatic contingencies are modeled as a Bernoulli Trial

Sequence, where contingencies are manifested by a development schedule slip or lengthened schedule, both increasing development cost.

The SET outputs quantify a spacecraft's physical- and cost-related characteristics at the system, module, subsystem, and component level; please refer to Ref. [111] for a detailed discussion of the SET outputs. There are four output aggregation levels: system, module, subsystem, and component. The outputs carry a prefix corresponding to the respective aggregation level they characterize and each successively higher level (more encompassing) output amasses the characteristics of the lower level outputs. For example, the system mass of a fractionated spacecraft is the aggregate mass of its respective modules. From the SET output metric space, this research chooses certain benefits and costs to examine, in particular system level outputs, which are recognized to be a subset of the entire cost-benefit (value) space for fractionated spacecraft.

Spacecraft Evaluation Tool Verification

The SET verification demonstrates the SET's mass and cost estimation accuracy and details of the verification can be found in O'Neill and Weigel [127].

8.3.6. Modeling Changes in Technology

Enabling technology innovation (change) is modeled using a discrete "S-curve" model, a selection based on findings from Szajnfarber *et al.* [146–149] who studied the pre-infusion (*i.e.,* before a technology is flight-ready) innovation history of six space science payload technologies. These works found that while the overall trend in performance improvements followed the conventional S-curve model, technical breakthroughs were punctuated and lead only to minor improvements. These breakthroughs specifically occurred at unpredictable intervals and their timing had important implications for capturing mission opportunities, thus suggesting that a *discrete* S-curve model for space technologies is most appropriate. The *continuous* S-curve model of Technology Innovation is given in Equation 15 (adapted from Seggern [150]).

Equation 15

$$S(t) = \left(s_{\max} - s_{\min}\right) \cdot \left(\frac{1}{1 + e^{(-t + c/2)}}\right)$$

Here, *S(t)* is the performance gain (innovation) in a technology over time, *t*. Depending on the technology, the S-curve can be mapped to an arbitrary timeline $\in [0,c]$ and performance gain bounds during that interval

135

$\in [s_{min}, s_{max}]$; here s_{min} and s_{max} is the technology performance at time 0 (*i.e.,* the beginning of the innovation period) and the theoretically best (or most desirable) performance at time *c*, respectively. The normalized S-curve given in Equation 15 represents a technology that improves exponentially but is subject to an initial ramp-up and axiomatic progression as
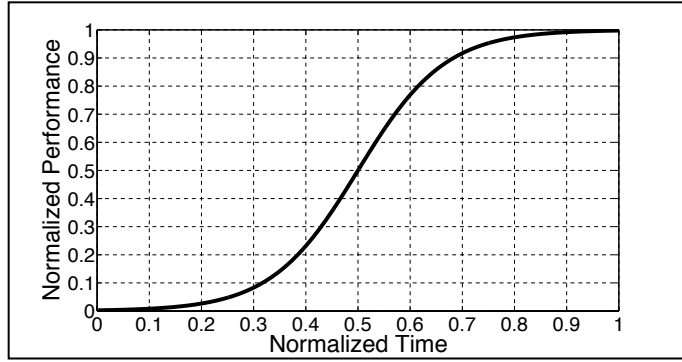
Figure 8-7. Continuous Innovation S-Curve.

best performance limits are approached; this is demonstrated by the normalized S-curve shown in Figure 8-7. For a given enabling technology, a discrete version of the innovation S-curve in Equation 15 is generated by assuming that technology performance breakthroughs occur according to a Poisson Process and that the depth of these breakthroughs follows the continuous S-curve model given the timing of the breakthroughs.

For a given spacecraft lifecycle assessment, the discrete innovation profile for each enabling technology is randomly generated by sampling the Poisson process to determine the inter-arrival of breakthroughs and, given these breakthrough timings, Equation 15 is then used to determine the breakthrough depths. An example of a randomly generated discrete S-curve for the Comm_CS_C&DH enabling technology is

provided in Figure 8-8, which depicts the relationship between the data transmission rate capability improvement during an arbitrary twelve-year innovation period. As observed in Figure 8-8, the inter-arrival times of discrete performance breakthroughs results in a plateau innovation profile (S-curve) over the
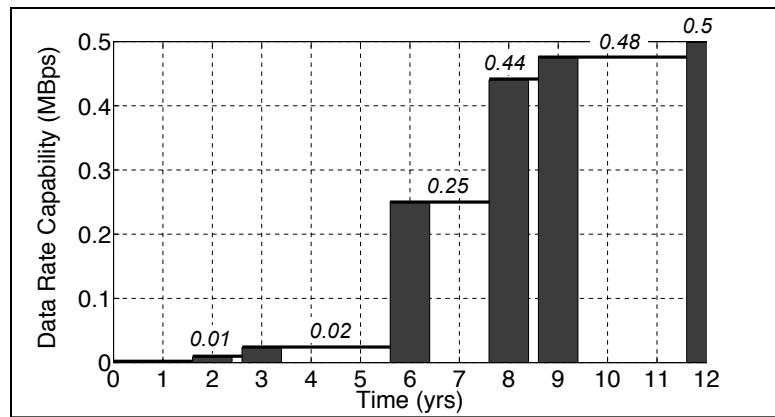
Figure 8-8. Discrete Innovation S-Curve.

assumed innovation period and this profile is representative of any randomly generated enabling technology profile.

136

In addition to gains in enabling technology performance, it is important to note that while the Comm_CS_C&DH and ADS_GNS enabling technologies are innovated, their reliability (along with that of the mission payload and other subsystems) is not assumed perfect and remains a constant source of risk in terms of spacecraft/module failure; this is further described in Ref. [127].

8.3.7. Innovation and System Performance

Innovation in the enabling technologies affects spacecraft performance and cost as follows. The Comm_CS_C&DH data rate transmission capability (performance) limits remote sensing spacecraft payload performance, measured by the resolution capability in pixels per meter (ppm), namely because this dictates the amount of information that can be transmitted from a payload to infrastructure module: the higher the data transmission rate, the higher the resolution capability on the payload module. The ADS_GNS performance does not directly affect spacecraft performance since it is concerned with the relative positioning and control of spacecraft modules. However, the benefit of improved control accuracy does reduce the minimum allowable distance between on-orbit modules. This has many direct benefits including a reduction in spacecraft mass and power supply requirements and therein the cost of spacecraft. Conversely, ConOps innovation affects spacecraft performance and cost through the time constants associated with rebuilding and replenishing modules during the time window considered. Since each replenishment scheme strongly influences the number of modules built over the time window, they each appreciably affect the resulting ToS, TWAP, and SLCC of a given spacecraft, which are the system outputs of interest in this case study.

8.3.8. Modeling Changes in ConOps

While there are numerous facets to spacecraft operation including launch and in-situ operation, ConOps innovation, or more generally change is assumed to occur through advances in replenishment strategies for spacecraft during the time window considered. Unlike innovation in technology, innovation in ConOps relies on several discrete replenishment strategies, some more advanced than others in terms of management complexity from the perspective of a spacecraft operator. Replenishment strategies are essentially rules to be followed when replacing modules if they fail and, given the possibility of coupled module failures due to sharing subsystem resources in fractionated spacecraft, these rules can lead to notable complexity in operating a given spacecraft. There are three replenishment schemes embodying the ConOps change, or innovation scale and a unifying rule within all of these schemes is that a shared resource

recipient module cannot be replaced unless its corresponding source module(s) are on-orbit, or ready for redeployment with the recipient module[20]. The following are the three types of ConOps of considered:

Existing ConOps – No Innovation

1. On-Demand: The *On-Demand* replenishment scheme is the simplest and existing ConOps strategy. This scheme begins rebuilding a module only after it is observed to fail on-orbit; thus, there will be a rebuild downtime before a module can be redeployed into service. Another subtle rule within this scheme is that if a source module for a recipient module currently being rebuilt fails, the recipient module waits until the source module is ready to be redeployed; this is required by the previously mentioned overarching rule for these replenishment strategies.

Advanced ConOps – Operational Innovation (Change)

2. Predicted: The *Predicted* replenishment scheme uses a replenishment rule for replacing modules before they actually fail on-orbit to ensure better continuity of spacecraft service over the entire time window. In the case where the expected design life of a module is less than the time window of interest, the predicted replenishment scheme hedges a bet that a module will fail after a certain time on-orbit and, subsequently, the "rebuild" of an eventually failed module on-orbit occurs while it is still on-orbit. The potential advantage of this approach is no, or less payload downtime than in the On-Demand scheme before a module is replaced after an observed failure. The specific rule used for this replenishment scheme is thus to begin rebuilding a given module within *n* years of observed on-orbit operation, where *n* is specific to the spacecraft architecture under consideration.

3. Threshold: The *Threshold* replenishment scheme is identical to the *On-Demand* scheme except that after a module fails, it is not rebuilt until an enabling technology performance breakthrough occurs. Unlike the Predicted replenishment scheme, which attempts to maximize the continuity (*i.e.,* duration) of payload service, this replenishment scheme attempts to maximize the on-orbit performance gains, thereby level of performance of a spacecraft over the given time window.

These three replenishment (ConOps) schemes will all lead to different spacecraft performance gains over the time window since they strongly influence the aggregate rebuild or "downtime" of a spacecraft during

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[20] This rule is required because recipient modules cannot operate without their source module counterparts; see O'Neill and Weigel [127] for further explanation.

the window. Thus, for a given architecture, the TWAP corresponding to each replenishment scheme will differ, perhaps substantially. From a programmatic perspective, the *Predicted* and *Threshold* schemes are advanced given the increase in complexity of managing not only coupled module failures but also coordinating replenishments according to the specific replenishment rule used by each of these schemes, which depends on the timing of innovation breakthroughs and gaming strategies. This is not the case when using the *On-Demand* scheme, which is relatively straightforward because of its one-rule strategy of "rebuild after an observed on-orbit failure and re-launch as soon as possible," which means modules are simply re-launched as soon as they are rebuilt.

8.4. Analyses

This section presents the case study analyses and each analysis presents a different perspective of applying the Tradeoff Analysis Framework in order to assess the impact of innovation on space system design and operation. Before the specific analyses are presented, the setup and key assumptions for the analyses are discussed.

8.4.1. Architectures

Two architectures are considered in the analyses, which are conceptually depicted in Figure 8-9. The first is a monolithic spacecraft and it belongs to the No Change category in the Change
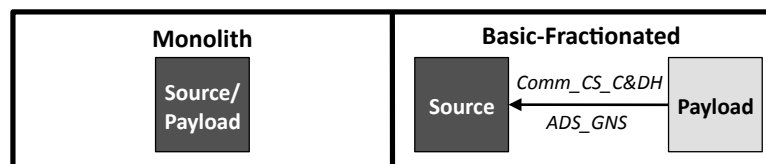
Figure 8-9. Spacecraft Architectures.

Taxonomy since this is the current architecture used to perform remote sensing missions. And the second architecture is a simple fractionated architecture (referred to as the basic-fractionated architecture) and it requires the development of enabling technologies (*i.e.,* innovation in technology) where any subsequent improvement in these technologies increases the performance of this spacecraft[21]. Given the use of current and new (innovative) ConOps, these two architectures will therefore collectively demonstrate the four types of change, or innovation in the Change Taxonomy.

8.4.2. Problem Scope and Assumptions

The major assumptions in the analyses are summarized hereafter. It is important to keep these assumptions in mind when interpreting the research results and the ensuing discussions in this case study.

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[21] Recall, that the two enabling technologies considered are the Comm_CS_C&DH and ADS_GNS shared resources.

- The two enabling technologies considered are the Comm_CS_C&DH and ADS_GNS shared resources. The performance bounds for these technologies, which are required to model their respective innovation, are [1e+02, 5.5e+05] Bps (higher magnitude is better) and [1, 150] m (lower magnitude is better), respectively.

- The time period for innovation in technology is fixed at 20 years, so after 20 years the Comm_CS_C&DH and ADS_GNS performance is the most desirable, given the performance bounds considered for each technology.

SPACECRAFT OPERATION

- The time window considered in the analyses is fixed at 30 years. This time window is the period beginning with initial spacecraft development through the end of the program, which includes operating spacecraft as well as rebuilding and redeploying spacecraft modules if they fail. This fixed time window is required to objectively compare the value proposition of architectures.

- Spacecraft initial development is 5 years and the time required to rebuild modules if they fail is assumed to be 3 years due to economies of scale (learning).

- A payload module can never be re-launched until its respective source module is ready to be launched with the payload module, or its source module is already on-orbit.

- Staged deployment can be used for fractionated spacecraft and this can involve up to three launch vehicles being used to deploy a spacecraft.

UNCERTAINTY

- 3,500 MCA trials are used to analyze a given spacecraft, which is that required for the expected value of TWAP, ToS, and SLCC (and thereby revenue) to converge.

- All lifecycle contingencies in the SET are considered, that is, launch vehicle reliability, human operator error, and on-orbit (technical) reliability (see SET discussion in Section 8.3.5).

REPLENISHMENT (CONOPS) STRATEGIES

- For the *On-Demand* replenishment scheme, modules are rebuilt immediately following an observed on-orbit failure.

- For the *Predicted* replenishment scheme, modules are rebuilt after 1 year of observed on-orbit operation, or after module failure if this happens before 1 year of operation.

- For the *Threshold* replenishment scheme, failed modules are rebuilt only after there is an innovation breakthrough in either the Comm_CS_C&DH and ADS_GNS resource. Since the innovation window is 20 years, after 20 years into the 30-year time window, the *Threshold* scheme is identical to the *On-Demand* scheme.

8.4.3. Overview of Analyses

The analyses performed in this case study are summarized hereafter and they will collectively evaluate all of the categories in the Change Taxonomy.

1. No Change Study: This analysis evaluates the monolithic spacecraft using the *On-Demand* ConOps scheme (1 assessment).

2. Technology Change Study: This analysis evaluates the fractionated architecture using the *On-Demand* ConOps scheme (1 assessment).

3. ConOps Change Study: This analysis evaluates the monolith using the *Predicted* ConOps scheme (1 assessment); the *Threshold* ConOps scheme is not applicable to the monolith.

4. Radical Change Study: This analysis evaluates the fractionated architecture using the *Predicted* and *Threshold* ConOps schemes (2 Assessments).

Therefore, in this case study, five analyses will be performed using the SET to quantify the impact of innovation in the design and operation of spacecraft performing remote sensing missions.

8.4.4. Analyses and Results

Before the results of the five aforementioned analyses are presented, the competing and complementary nature of tradeoffs amongst the system outputs is analyzed. This analysis specifically helps to identify the driving tradeoffs, or lack thereof, for determining value in this case study.

TRADEOFF RESOLUTION

Principal Component Analysis (PCA) is used to determine the competing and complementary nature of the system outputs and therein the sources of value (*i.e.,* revenue and cost) [86]. PCA is a useful method for quantifying the correlation (or lack thereof) amongst the system outputs and representing the resulting

system output tradeoff hyperspace in a reduced-order (*e.g.,* two-dimensional) space. This representation enables the most important system output tradeoffs to be readily identified.

In this case study, PCA was used to analyze the relationship amongst TWAP, ToS, SLCC, and Revenue, specifically using the data from the Technology Change Study described in Section 8.4.3. After applying PCA, it was found that one and two principal components captured 84.0% and 99.99% of the variability in the system output space, respectively, thus implying that the original outputs comprising the tradeoff hyperspace can be fully captured in a two-dimensional principal component space. The corresponding two-principal component representation of the system output space is shown in Figure 8-10, which is normalized on the range of [-1, 1]. The red scattered data in Figure 8-10 are the system outputs mapped to the principal component space corresponding to the 3,500 MCA trials used to assess the Technology Change category (*i.e.,* the basic fractionated spacecraft using the On-Demand replenishment scheme). In Figure 8-10, the black vectors are the ensuing
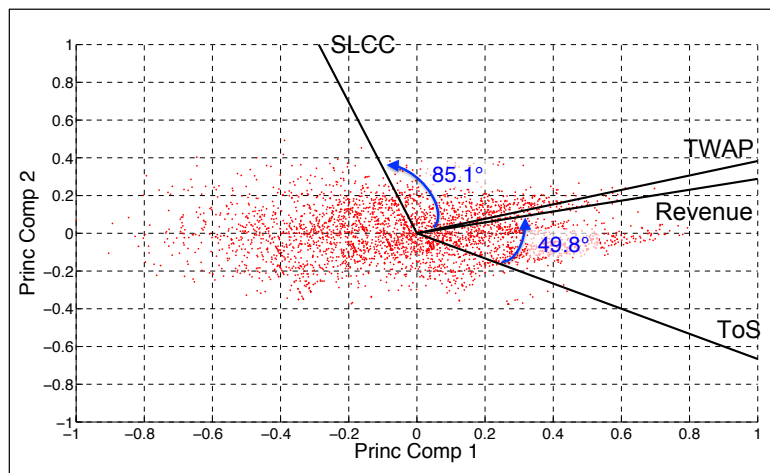
Figure 8-10. PCA of System Output Space.

system output dimensions mapped to the principal component space. The two principal components in Figure 8-10 are composite variables of the four outputs and therefore the angular proximity of a given tradeoff vector to a principal component axis is indicative of its relative contribution to that component. For example, in Figure 8-10 Revenue is close in proximity to the first principal component (*i.e.,* the x-axis) by an angular offset of 16.07°, therefore it contributes proportionally the most to the first principal component dimension.

The relative angular displacement amongst the four output dimensions shown in Figure 8-10 by the black vectors can be used to determine the complementary and competing nature of these outputs in relation to one another. Specifically, as the angular offset between any two dimensions nears 0°, 90°, and 180°, the two outputs become perfectly complementary, neutral, and perfectly competing, respectively, *assuming* that an increasing magnitude in an output is more desirable, which is the case for all of the outputs in this case

study except for the SLCC output. Complementary output dimensions are aligned such that increasing the value of one increases the value of the other whereas competing dimensions (*i.e.,* tradeoffs) demonstrate the converse of this situation. And neutral output dimensions are uncorrelated. Given the relative angular offsets amongst the tradeoff dimensions in Figure 8-10, the following can be concluded:

1. TWAP and Revenue are complementary (angular offset of 4.88°)
2. SLCC is nearly neutral to TWAP and Revenue (angular offset of 85.1°)
3. ToS and SLCC are nearly opposing (angular offset of 139.8°), but since reducing SLCC and increasing ToS is desirable, this makes ToS and SLCC more complementary than they are competing

Using PCA to draw the above conclusions provides valuable insight into the system outputs and ensuing important tradeoff dimensions in this case study. For example, TWAP and Revenue were found to be complementary and these two outputs are also complementary with ToS (more than they are competing with ToS). Intuitively, this makes sense since as shown in Equation 13, Revenue is dependent on TWAP and ToS, and therefore Revenue increases with a higher TWAP, which also happens to increase (to a first-order) with ToS. Thus, TWAP, Revenue, and ToS can be treated as complementary, that is, improving one will likely improve the others, in terms of stakeholder value. And with regard to SLCC, it is desirable to decrease cost and since SLCC is close to being antiparallel to ToS, SLCC and ToS are closer to complements, that is, reducing SLCC increases ToS[22]. The reason for the decrease of SLCC with an increase in ToS is that the cost of spacecraft operation is relatively small compared to the cost of rebuilding and re-launching spacecraft, hence, a higher ToS implies less rebuilds and thereby a lower SLCC. Lastly, TWAP and Revenue are neutral to SLCC. The reason for this is that TWAP depends on a combination of improvements in performance (resolution), via enabling technology enhancements, and the sequencing and timing of spacecraft deployments, which are subject to potential launch vehicle failures. Thus, a given TWAP value can be manifested through numerous developmental and operational scenarios for a spacecraft, each corresponding to different SLCC values.

In summary, the lesson learned from the PCA of the outputs in this case study is that in order to maximize value, maximize TWAP since this increases revenue and does not necessarily lead to an increase in SLCC.

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[22] Note: two opposing tradeoffs would be competing if it was desirable to increase the magnitude of both, but this is not the case with SLCC and ToS.

Thus, any approaches to design and operate spacecraft that increase TWAP are likely to increase Revenue without appreciably changing SLCC and thereby increase value. While this conclusion is based on the data from the Technology Change study described in Section 8.4.3, the generalization of this conclusion to the results of the other innovation studies is supported in Appendix C, specifically through the comparison of the PCA-derived system output trends for all three ConOps scenarios with the fractionated spacecraft.

VALUE PROPOSITIONS

The value propositions in this case study are summarized in Figure 8-11, which shows the four categories of innovation assessed using monolithic and fractionated spacecraft and the three redeployment and replenishment schemes. (Recall that the monolith cannot use the Threshold scheme.) All units in this figure are in units of FY11$M. As seen in Figure 8-11, for each analysis, the inter-quartile range (*i.e.,* 25th, 50th, and 75th percentiles) of value is provided. A sample value histogram corresponding to the Technology Innovation study is shown in Figure 8-12, where the sample size is 3,500 trials.

Figure 8-11. Value Propositions (Case Study 3).
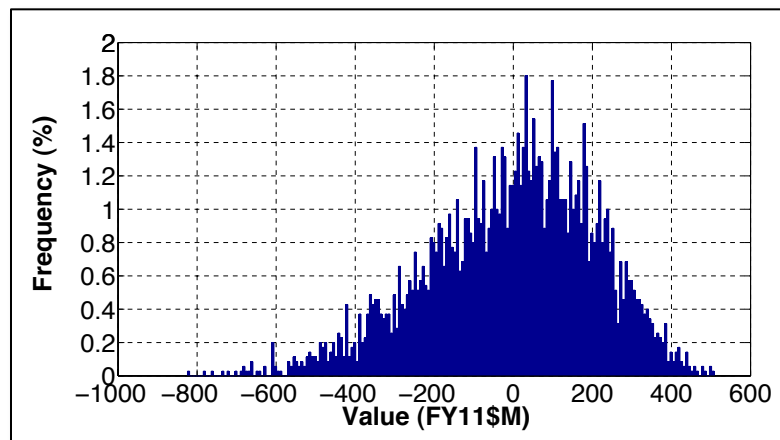
Figure 8-12. Sample Value Histogram.

sample size is 3,500 trials. The resulting distribution appears to be weak lognormal distribution, although this is not necessarily the case for the value distributions corresponding to the other change analyses.

144

Therefore further statistical validation of this distribution is required to verify its log-normality. Examples of representative operational histories corresponding to the fractionated spacecraft and the three ConOps scenarios can be found in Appendix D.

In examining Figure 8-11, one consistent trend is that the Predicted replenishment scheme offers more value than the On-Demand and Threshold schemes, regardless of architecture. Additionally, regardless of ConOps, the fractionated spacecraft value is consistently less than the comparable monolithic spacecraft. In fact, the median value of fractionated spacecraft is negative (or close to 0) whereas the monolith always yields a positive median value. The reasoning for this trend is discussed in more detail in Section 8.5.

The value results shown in Figure 8-11 effectively explore the "corners" or extremes of potential ConOps, thus defining the fractionated value boundaries in this case study. The isolation of the ConOps corner points allows for inferences to be made about fractionated spacecraft value that span the space of potential ConOps (replenishment) schemes for these spacecraft. To demonstrate these boundaries, Figure 8-13 shows the median Value versus ToS, which is complementary with TWAP, for the basic fractionated spacecraft given all three replenishment scenarios. As seen in Figure 8-13, the Threshold scheme defines the lower bound for ToS and Value. This is because with this scheme modules are not replaced until there is an improvement in one of the enabling technologies, so in these scenarios spacecraft modules see the

Figure 8-13. ConOps "Corner" Points.

longest downtime and thereby the lowest ToS and value delivery. The upper bound of ToS and Value is established with the Predicted replenishment scheme since this scheme often provides continuous on-orbit payload service and thus the highest ToS and value delivery. Lastly, the On-Demand scheme ends up being slightly higher than the Threshold scheme in terms of ToS, but is nearly identical in terms of value; the explanation for this is discussed in more detail in Appendix D.

THE VALUE ROBUSTNESS ARGUMENT

One of the longstanding arguments as to the potential benefit of fractionated spacecraft relative to a comparable monolith is that when both are subject to the same lifecycle contingencies (*e.g.,* launch or on-

145

orbit failures), fractionated spacecraft will have more value robustness, that is, a narrower distribution of expected value (*i.e.,* less value-variance). In this case study, several lifecycle contingencies were considered and these include: human (operator) error, launch vehicle reliability, technical (hardware) reliability, and programmatic issues. Given that the monolithic and fractionated spacecraft in this case study were equally subjected to these contingencies, the remainder of this section will examine the value-at-risk, or value robustness argument for fractionated spacecraft *in the context* of innovation, which makes a unique contribution to the value robustness argument for fractionated spacecraft.

The value-variance corresponding to the five analyses performed in this case study is shown in Figure 8-14, which presents the order-statistic, five-number summary for each type of change, or innovation examined. Starting from the top
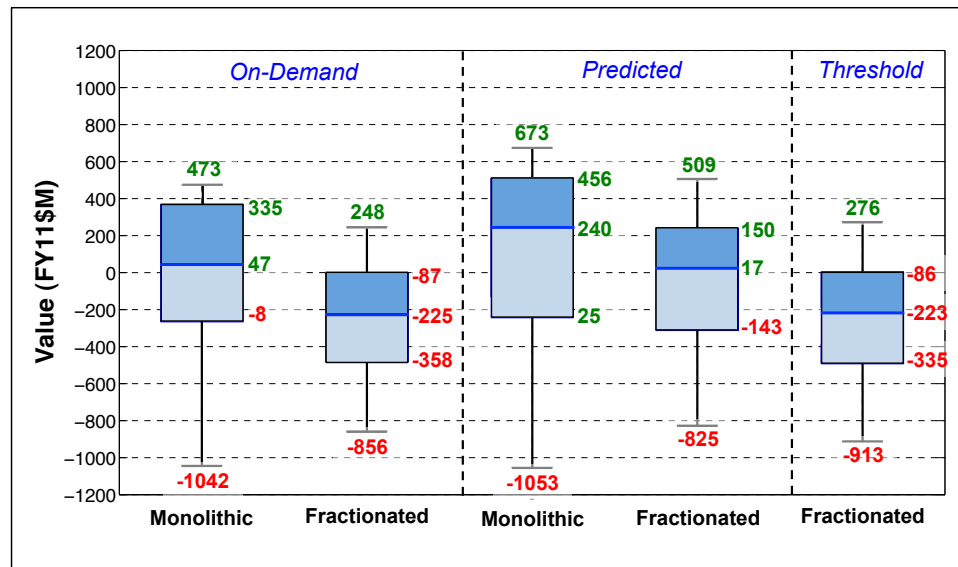
Figure 8-14. Value Percentiles.

of each "box-and-whisker" plot in Figure 8-14, the percentiles are indicated by horizontal lines and are the maximum (100th), 75th, 50th (median), 25th, and minimum (0th) percentiles. One measure of the value-variance of spacecraft is the inter-quartile range, which is the range between the 75th and 25th percentiles; this range is shown in Figure 8-14 by the blue shaded boxes. As can be seen for the On-Demand and Predicted replenishment schemes, even though the inter-quartile range of the fractionated spacecraft is lower (*i.e.,* less valuable) in an absolute sense, fractionated spacecraft have a tighter variance by 72 and 138 FY11$M relative to the comparable monolith with the On-Demand and Predicted ConOps schemes, respectively. This leads to a reduction in value variance of 21% and 32% when using fractionated spacecraft with the On-Demand and Predicted ConOps, respectively. Hence, the results from this case study support the conclusion that fractionated spacecraft are more value-robust, even given the innovation investigation emphasis in the case study.

146

An alternative perspective of the differing value robustness of monolithic and fractionated spacecraft is demonstrated by comparing their respective value-at-risk and gain (VARG) curves, which are their respective value cumulative distribution functions (cdf's); these are shown in Figure 8-15 and Figure 8-16. In these figures, the dotted and solid lines represent the median value and value cdf, respectively, and the color red and blue represents the monolithic and fractionated spacecraft, respectively. For a given spacecraft, the relative portion of the cdf that is negative and positive in terms of value measures the value-risk and value-gain, respectively. So, for example, the fractionated spacecraft using the
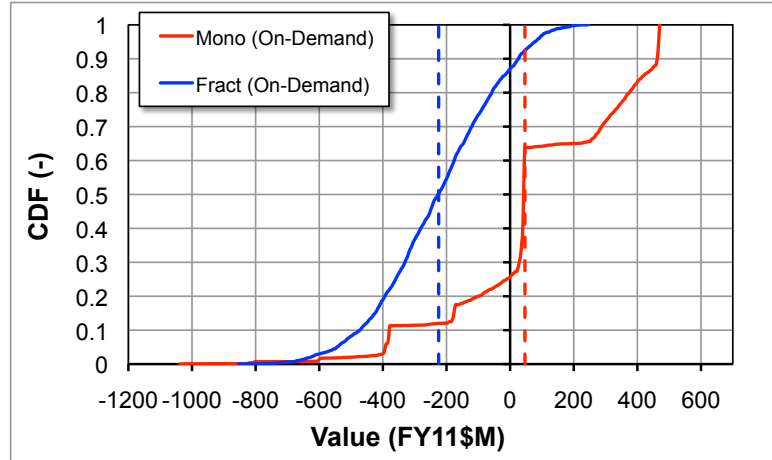
Figure 8–15. Value-at-Risk and Gain Curves (On-Demand).
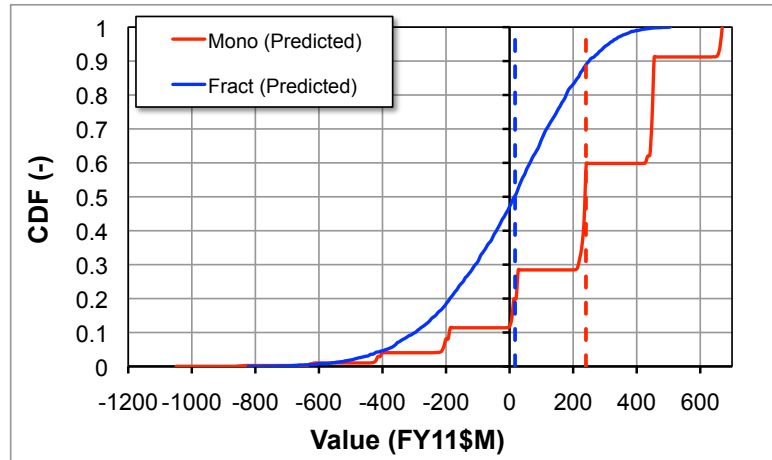
Figure 8–16. Value-at-Risk and Gain Curves (Predicted).

On-Demand scheme in Figure 8-15 is predominantly a value-risk since very little of the cdf falls in the positive value region. Lastly, the median line will indicate whether the spacecraft has a greater total value-risk or value-gain by its respective sign (relative to 0); this median value is that reported in Figure 8-11 for a given architecture.

A few insights can be gained from the VARG curves. First, the monolithic cdf's are punctuated, which is indicative of the discrete failures and replenishments of the monolith; each step in the monolith cdf corresponds to a unique number of failures and hence replenishments and, since the cost of the launch vehicle used by the monolith is about $150 million dollars, the steps in value are noticeable. Conversely, fractionated spacecraft have smooth cdf's owing to the fact that there are numerous combinations of deploying and operating separate modules as well as launching them on multiple launch vehicles, which

147

ultimately yields a higher number of unique deployment and operational scenarios and hence revenue and cost combinations (*i.e.,* value). Since, the cdf's all begin at roughly the same value (about -600 FY11$M), comparing the span of a given spacecraft's cdf as it goes from 0 to 1.0 along the y-axis is also a measure of its value-variance (or robustness) since this indicates the "tightness" of a spacecraft's distribution of potential value. Correspondingly, in Figure 8-16 and Figure 8-15, the fractionated spacecraft demonstrates less value-variance than the comparable monolith, despite the value-risk outweighing the value-gain for the fractionated spacecraft in the On-Demand case, and the value-gain slightly outweighing the value-risk in the Predicted case.

In summary of the findings from the monolithic and fractionated spacecraft value robustness analysis, the following can be concluded. First, innovation in technology leading to the development of fractionated spacecraft creates more value-risk than value-gain as compared to not innovating (*i.e.,* using monolithic spacecraft). And regardless of technological innovation, using the Predicted ConOps scheme, as compared to using the On-Demand and Threshold schemes, reduces the value-risk of a spacecraft. Despite the consistently less positive value potential of fractionated spacecraft as compared to monoliths, they demonstrate notable reductions in the value-variance about their respective expected value, thus implying that they have more value robustness than a comparable monolith, given an equivalent subjection of these spacecraft to lifecycle contingencies.

8.5. Discussion

The objective of this case study was to evaluate the impact of innovation on the design and operation of spacecraft performing remote sensing missions. The specific innovation considered was the development of, and improvements in, enabling technologies, which are required for fractionated spacecraft, as well as changing replenishment strategies (ConOps) for both monolithic and fractionated spacecraft. The two stakeholders of interest in this case study were the spacecraft developers and the operators, the former being responsible for developing and manufacturing a spacecraft and the latter being responsible for operating the spacecraft. The value proposition for these two stakeholders differs in that the spacecraft developer does not receive any direct benefit from the spacecraft operation other than demonstrating a successful mission, whereas the operator derives a direct benefit from the spacecraft operation in terms of acquiring images of the earth. Subsequently, the developer has no direct value-based incentive to participate and, thus in this case study, the developer and operator were combined into one stakeholder who collectively bears the costs of, but also benefits from, a spacecraft's operation.

The specific insights regarding the impact of innovation on remote sensing spacecraft are discussed first in this section followed by a discussion of the unique implementation insights gained from applying the Tradeoff Analysis Framework in this case study.

8.5.1. Case Study Insights

This case study and its ensuing results provide a first glimpse into the impact of innovation on the remote sensing mission paradigm, specifically the value of fractionation in this mission context. The section begins with discussing the role and subsequent value of replenishment strategies for remote sensing missions and then discussed the trends in the system outputs and value propositions. This section concludes with discussing the implications of the assumptions made in the case study as well as the impact of the case-specific insights gained herein in terms of the past and future of the DARPA System F6 program.

REPLENISHMENT (CONOPS) STRATEGIES

The first important insight is the role of replenishment strategies for remote sensing spacecraft. The current or datum strategy is the On-Demand scheme whereas new, more complex replenishment strategies include the Predicted and Threshold schemes (see Section 8.3.8 for a description of these schemes). As was found in the results, the Threshold and Predicted schemes define the "corner points" in terms of potential value for fractionation (see Figure 8-14). The Threshold scheme generates the least value because the emphasis is on redeploying modules only when technological innovation occurs (*i.e.*, improvements in the enabling technologies). Thus, with this replenishment scheme the ToS tends to be low and, despite the high gains in performance with each new spacecraft module deployment (and hence revenue potential), the ToS dominates the revenue generation and so these spacecraft prove relatively invaluable. Conversely, the Predicted replenishment scheme yields the best case scenario for value through seamlessly replacing modules on-orbit by building them beforehand, thereby maximizing ToS while still seeing gains in spacecraft performance due to innovation and hence revenue potential. However, the major disadvantage of this approach is that redeployed modules will often lack the latest innovation since they are prebuilt, potentially years before a module is ever observed to fail on-orbit. Despite this limitation, the high ToS with the Predicted replenishment strategy dominates the revenue generation and hence yields a high value as compared to that yielded with the other strategies.

149

The remaining insight regarding spacecraft innovation in ConOps is that, interestingly, the On-Demand scheme is very similar to the Threshold scheme in terms of spacecraft value. The dynamic between these two replenishment strategies, as explored hereafter, provides an interesting glimpse regarding the relative value of these approaches. In this case study, a three-year module rebuild time was assumed whereas the enabling technology breakthrough inter-arrival time was, on average, about two years. If the rebuild time of modules is similar to the average inter-arrival time of enabling technology breakthroughs, then the On-Demand and Threshold schemes are going to very similar, if not indistinguishable in terms of spacecraft value delivery. And as the technology breakthrough inter-arrival times become much larger, and shorter than the module rebuild time, the On-Demand replenishment scheme will become more valuable and similar in value to the Threshold replenishment scheme, respectively. The reason for the former is that when the technology breakthrough inter-arrival times are longer than the time required to rebuild a module, on average, this will result in excessive module downtime while waiting for a technology breakthrough and thereby a loss in value. However, in the opposite sense, as the breakthrough inter-arrival times become shorter than the module rebuild time, the constraint on rebuilding and redeploying modules will be the rebuild time, which cannot be shortened given the assumptions made in this case study, and hence the On-Demand and Threshold schemes converge in terms of value delivery.

Therefore, in summary of the findings regarding ConOps innovation, or more generally change for remote sensing spacecraft, the Predicted scheme consistently yields the most value, regardless of architecture (monolithic or fractionated). The lesson learned from this conclusion is that even though a replenishment scheme may not optimize performance gains in technology, which is the driver for gains in revenue, the driver of value is ToS, which is maximized by keeping the payload module(s) on-orbit, and the Predicted replenishment scheme does exactly this. And since the cost of operating spacecraft is relatively low compared to the cost of rebuilding and redeploying them, the more time on-orbit a spacecraft has, the more value it can deliver, even if the spacecraft performance is suboptimal at the moment given advances in technology. The results from this case study can therefore be extended to tentatively support the use of spare modules either on the ground or in space to immediately replace failed modules in a fractionated spacecraft in order to maximize its respective value. However, further investigation into maximizing value as it depends on the spacecraft architecture and replenishment schemes will need to be conducted to generalize this tentative conclusion.

The other insights gained from this case study are with regard to the potential value of innovation in the remote sensing mission paradigm. The results leading to these insights provide one perspective for understanding the impact of innovation on remote sensing spacecraft design and operation. In terms of system output tradeoffs, it was found that TWAP and ToS were complementary and both were neutral to SLCC. Since SLCC was relatively independent of TWAP and ToS, there was an absence of strongly competing system output tradeoffs observed in this case study, which was not known before performing the case study, hence demonstrating one of the benefits of using analytical methods such as PCA to analyze the system output/value space (see Section 8.4.4). The reason for the neutrality of SLCC to TWAP and ToS is that there are a numerous manifestations of a spacecraft's operational history corresponding to a given TWAP and ToS value and each of these can have appreciably different costs given the contingencies considered for spacecraft in this case study (see Section 8.3.5). In terms of value, spacecraft Revenue was found to be complementary to TWAP and ToS, which intuitively makes sense, and thus Revenue is relatively neutral to SLCC. So in terms of the value proposition, the key to maximizing value is to maximize revenue, or TWAP and ToS.

Recall that in this case study, innovation in technology leads to fractionated spacecraft and subsequent performance improvements in these spacecraft. However, this source and type of innovation proves to be undesirable in terms of value relative to the current remote sensing mission paradigm, namely, monolithic spacecraft. As shown in the case study results, even when accounting for uncertainty, fractionated spacecraft have 225 FY11$M *less* value as compared to the monoliths value of 47 FY11$M, a 272 FY11$M loss in value through innovation in technology. This loss in value would have further increased had the case study included the cost of research and developing the enabling technologies, which was assumed to be borne elsewhere. As discussed in the previous paragraph, regardless of spacecraft architecture, the Predicted replenishment scheme increases value delivery. However, despite fractionated spacecraft providing positive value with the Predicted scheme, the monolith still provides 223 FY11$M more value than the fractionated spacecraft in using this scheme. Therefore, regardless of replenishment scheme, since the value offered by fractionated spacecraft is negative (or close to it with the predicted scheme), this demonstrates a clear value-positive preference for monolithic spacecraft given a current-day evaluation of the value potential of fractionated spacecraft, given the assumptions made in the case study.

Based on the quantitative results of this case study summarized in the previous paragraph, there are two interesting discussion points regarding the impact of innovation. The first is with regard to the absolute value of innovation, which depends heavily on the revenue model used in the case study (see Section 8.3.3). Recall, that this model was derived from the current market (value) for acquiring images of the earth and while there is likely uncertainty in the revenue model, it does demonstrate the current cost-competitive nature of the earth imaging acquisition market. Correspondingly, as shown in the results, with or without innovation, the profit margin (if any) for spacecraft is not particularly large, specifically, no more than a 240 FY11$M profit margin was observed for remote sensing spacecraft. Therefore, the cost-competitive nature of the earth image acquisition market increases the demand for innovation to become immediately valuable in order to maintain positive profits. And, unfortunately, this was not demonstrated in this case study since innovation in the enabling technologies did not progress rapidly enough for fractionated spacecraft to stay value-competitive with the comparable monolith, which yielded marginal profits to begin with. Therefore, the conclusion drawn from this case study in terms of absolute value delivery is that it is currently more valuable to use a monolithic spacecraft and not pursue innovation. There could be an arguable tradeoff between monolithic and fractionated spacecraft if fractionated spacecraft yielded positive value, but since the value offered by fractionated spacecraft is negative (or close to it with the Predicted scheme), this demonstrates a clear value-positive preference for monolithic spacecraft based on these case study results and the assumptions made within the case study.

In summary, the focal lesson learned from this case study is that the impact of technological innovation in the remote sensing mission paradigm is a negative one, owing to the fact that the enabling technologies are not space-qualified to the level of performance and reliability needed for fractionated spacecraft to presently stay value-competitive to a monolith. However, the impact of innovation in operations is positive as it can increase value delivery, regardless of spacecraft architecture. Therefore, in summary, if fractionated spacecraft were to be deployed today, their respective enabling technologies may limit their potential value delivery *until* they are flight-ready at the desired level of performance and reliability. Once this is the case, many of the other benefits of fractionation demonstrated in this case study and the relevant literature such as the lesser value-variance (*i.e.,* higher value robustness) of fractionated spacecraft might come to fruition.

The assumptions made in the case study are summarized in Section 8.4.2 and they drive the observed results. Of the assumptions made (see Section 8.4.2), the only that are likely to change the results and insights gained in the case study are the time-window considered, the performance bounds of the enabling technologies, and the inter-arrival of technology breakthroughs. The time-window is the period during which spacecraft are initially developed, deployed, operated, rebuilt, and redeployed. An infinite time-window would eliminate the adverse value-effect of the innovation buildup period, during which the enabling technologies cause fractionated spacecraft to have inferior performance compared to a monolith. The other important assumptions are the performance bounds of the enabling technologies, in particular, the initial or present day performance bound. Intuitively, if the initial performance is near the desirable performance, fractionated spacecraft will be immediately value-competitive with monoliths, but the reality is that the enabling technologies are presently immature, given their respective definitions in this case study. Thus, interesting future research for this case study would be to investigate the sensitivity of the enabling technology bounds (along with the breakthrough inter-arrival times) to gain a clearer perspective of the potential value of fractionation, given different technological innovation progressions (scenarios).

CASE STUDY INSIGHTS AND THE DARPA SYSTEM F6 PROGRAM

The motivation of this case study was to paint a more realistic picture for future fractionated spacecraft investors through, in part, examining the affect of innovation on their potential value delivery. In accounting for uncertainty in value, the results from this case study suggest that fractionated spacecraft are less valuable than comparable monoliths. In addition, the results suggest that if fractionated spacecraft were to be deployed today, their enabling technologies may be the limiting factor in terms of their value delivery. Despite this, once the enabling technologies eventually mature to their desired level of performance and reliability, fractionated spacecraft are likely to stay value-competitive to comparable monoliths, specifically because of their higher value robustness (*i.e.,* less variance in value) relative to comparable monoliths, as was demonstrated in this case study. This observation supports the overhaul of the DARPA System F6 Program in the fall of 2009 to focus on the development the "F6 technology pillars," which includes the development of some of the enabling technologies considered in this case study as a prerequisite to deploying fractionated spacecraft. This was not emphasized in the first phase of the program but has now become one of its cornerstones. The current System F6 program therefore seems to align itself with the recommendations of this case study to focus on maturing the enabling technologies until they no longer

limit the capabilities of fractionated spacecraft relative to a comparable monolith. Once this is achieved, fractionated spacecraft may offer the unique sources of value (relative to a comparable monolith) as hypothesized and supported in the fractionated literature (see Section 8.2).

In addition to the challenge of justifying fractionated value, DARPA's current fractionated spacecraft demonstration approach may also prove challenging, which requires the participation of a third party spacecraft (module) developer to be responsible for building and integrating a module with a fractionated spacecraft already on-orbit[23]. As was discussed in Section 8.3.2, when the developer and operator of a spacecraft are separate (organizations), there is a misalignment of the value proposition, so much so that the third party developer has very little, if any, direct value-based incentive to participate in the operation of the spacecraft. This is primarily due to the fact that the developers bear most of the financial risk and receive very little, if any, of the direct benefits from the spacecraft operation. This situation mirrors the current value proposition for the third party module developers who DARPA is interested in having participate in the F6 program, which may substantiate some of the challenges that lie ahead in garnering their participation for the program.

<u>FUTURE RESEARCH</u>

While this case study provides a glimpse into the impact of innovation, specifically the development and improvement of fractionated spacecraft, there are many areas for future research that would be beneficial for understanding the potential value of fractionated spacecraft. First, many assumptions were made regarding the enabling technologies and their progression (improvement over time). These assumptions greatly influence the value offered by fractionated so it would be valuable to explore these assumptions to better understand the sensitivity of value to innovation. The second area for future research would be examining additional fractionated architectures. Only one fractionated architecture was considered in this case study, however, there might be other potentially valuable fractionated architectures worth analyzing. For example, a space-based, fractionated interferometer may prove quite valuable despite the conclusions drawn about fractionation in this case study or, alternatively, examining the use of redundant infrastructure modules in fractionated spacecraft may prove valuable. Lastly, analyzing other instances of coupled innovation through new ConOps (replenishment strategies or other operational scenarios) and

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[23] The first party such as DARPA or some other organization will supply these other modules and they are ultimately responsible for operating the spacecraft.

new/different enabling technologies are likely to prove insightful for understanding impact of innovation on the remote sensing mission paradigm.

8.5.2. Framework Implementation Insights

This section discusses the implementation insights gained through applying the Tradeoff Analysis Framework in this case study to assess the impact of innovation on remote sensing mission spacecraft. The section is parsed into discussing uncertainty in the framework and the subsequent modifications required to the framework to address this uncertainty.

UNCERTAINTY IN THE FRAMEWORK

The various sources of uncertainty in the framework were an important consideration in this case study as well as the affect of this uncertainty on the framework execution and representation of results. Thus, the first implementation insight deals with uncertainty in the framework, specifically their respective origin(s) and downstream implications in terms of the framework execution. The third case study served as the platform for developing insights about uncertainty its implications, specifically because there were several key sources of uncertainty that arose in the system and external factors in the framework; thus, in this case study, a combination of two sources of uncertainty (*i.e.,* layered uncertainty) had to be dealt with. Any uncertainty in the framework will ultimately be reflected in the value proposition, which, recall, is conveyed back to the analyst and stakeholders of interest. Therefore, alterations to the framework must be made in order to account for sources of uncertainty and the result is the introduction of new challenges in executing the framework, which are summarized in Table 8-2. The first of these challenges is determining the required alterations needed to the framework in order to capture/quantify uncertainty; this

Challenges
Modifications to the framework
Visualization

Table 8-2. Challenges Introduced via Uncertainty and Constraints.

is obviously very dependent on the source(s) of uncertainty and their underlying representation. This challenge, as addressed in this case study, is discussed next.

MAKING MODIFICATIONS TO THE FRAMEWORK

In this case study, there were two main sources of uncertainty in the framework: the external factors and the system model (see Section 8.3.5). The uncertainty in the external factors arose because of the various lifecycle contingencies affecting spacecraft such as launch vehicle reliability and human operator error. Conversely, within the system component of the framework, the cost model contained uncertainty because

155

it relies on parametric (mass-based) CER's, so there is an associated level of confidence in the SLCC system output. The introduction of this uncertainty, specifically from the external factors, required the framework to be implemented differently in order to capture this source of uncertainty. Figure 8-17 summarizes the changes made to the framework in this case study, which consisted of using a Monte Carlo Analysis (MCA) to sample the system output space for a given architecture. This random sampling method was chosen because the external factors are manifested by statistical models of the various sources of contingencies in a

Figure 8-17. Framework Implementation Changes.

spacecraft's respective lifecycle. As such, the MCA executes the system transform (see Section 4.3.1) repeatedly for a given architecture in order to sample the corresponding system output space.

The spacecraft cost model uncertainty can be captured through putting quantifiable tolerances on each SLCC value; this can be done since the uncertainty in the cost model is quantifiable via the parametric, mass-based CER's employed. While cost model uncertainty is not conveyed in the results of this case study, examples showing this source uncertainty in combination with external factor uncertainty (as captured via a MCA) can be found in Ref. [127].

There are two important considerations when modifying the framework to account for uncertainty. First, any modifications to the framework must preserve the original flow of inputs and outputs in the framework. The inherent utility of the framework depends on its underlying mechanics (functionality) such as the system transform (see Section 4.3.1), and these core functions of the framework must be maintained in order to realize its intended utility. A good example of making modifications to the framework while maintaining its underlying functionality can be found in this case study where a MCA was effectively wrapped around the system transform but did not change the underlying inputs or outputs of this
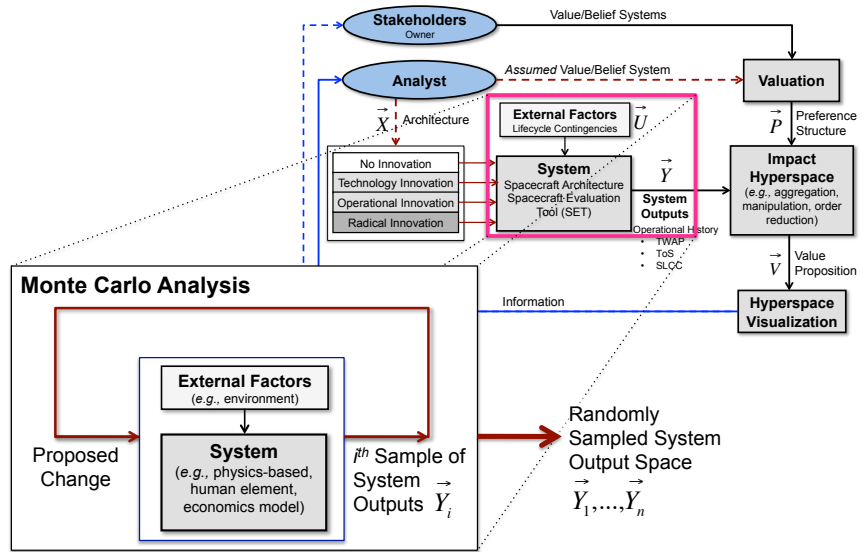
framework element. The second consideration when making modifications to the framework is whether these modifications still allow the framework to be used to meet the original objectives of the framework application. Modifications can disrupt the framework execution and so care needs to be taken in making modifications in order to meet the original objectives set forth for the framework usage, given the application of interest. For example, if using a MCA increases the time required to execute the framework, so much so that it becomes intractable to analyze the system of interest, then the MCA modification to the framework is inappropriate since the original objectives of the framework execution cannot be achieved.

REPRESENTING (VISUALIZING) UNCERTAINTY

The second and remaining framework implementation insight that will be discussed deals with representing uncertainty. When two or more sources of uncertainty exist in the framework, it leads to layered uncertainty in the value proposition, since each source of uncertainty must be explicitly accounted for through value. Layered uncertainty may lead to challenges in representing value, which may not be trivial. The remaining challenge due to uncertainty in the framework is therefore representing uncertainty, specifically through the hyperspace visualization component of the framework. Depending on the methods used to quantify uncertainty, the task of visualizing the resulting value proposition(s) may become more difficult than visualizing deterministic data. Uncertainty in the framework, regardless of how it is quantified, will introduce a tolerance (or confidence) in the value proposition and this tends to make the visualization of this proposition more complex through requiring a single metric value to be represented with respect to its range of possible values. While this challenge remains very specific to a given framework application, an important source of guidance for visualizing uncertainty in the framework outputs is Miller's Cognition Limitation Rule (aka "Miller's Law). Miller's Law states that people (*e.g.,* stakeholders) are limited to simultaneously trading (managing) in 7 +/- 2 dimensions [151], although more recent research regarding this landmark study suggests that Miller's estimate is high and that people are more likely limited to simultaneously trading in 4 dimensions [152]. Uncertainty or not, Miller's Law serves as constructive guidance for the maximum practical number of dimensions that can simultaneously visualized, if the information is to be effectively understood and used by the analyst and/or stakeholders in the framework.

In terms of visualization, the solutions offered in this case study include: a composite variable representation via Principal Component Analysis (Figure 8-10); a histogram, or probability density function (Figure 8-12); an order-statistic, five-number summary (Figure 8-14); and value-at-risk and gain (VARG) curves, or

cumulative distribution functions (Figure 8-15). While all of these approaches are valid for visualizing uncertain outputs, the most common technique for representing uncertain system outputs is to simply use the mean trends in the system outputs and ensuing value proposition as shown in Figure 8-11. This visualization approach, however, abstracts the potential system output space to a single number, therein losing the important insights to be had from the distribution of these framework outputs. Subsequently, the four previously mentioned visualization approaches were explored in this case study for representing value uncertainty. While these approaches to visualizing uncertainty are not all-inclusive (see Appendix A for other potential visualization options), they demonstrate the common tradeoff between abstract and detailed representations of uncertain metrics (outputs) and therein the limitations of visualization in terms of the volume of uncertain information that can be effectively conveyed at one time.

EXPLORING THE SYSTEM OUTPUT TRADEOFFS WITH PRINCIPAL COMPONENT ANALYSIS

Principal Component Analysis (PCA) was used in this case study to analyze the tradeoff hyperspace comprised of the system outputs of interest in this study. A relevant discussion about the use of PCA in the context of the Tradeoff Analysis Framework can be found in Section 6.5.2.

9. DISCUSSION

The focus of this section is the key insights gained through this research through applying the Tradeoff Analysis Framework. This section begins with discussing the potential opportunities to extend this research in relation to the tangible outcomes of this research, namely the Tradeoff Analysis Framework and Change Taxonomy. Then, the core insights and ensuing contributions of this research are presented followed by a discussion of the scope of problems that might be analyzed with the framework. It is important to recognize that the framework opportunities and ensuing contributions of this research are purposefully independent of the specific application of the framework given the intention of this research to provide a general, or system-agnostic approach for analyzing tradeoff hyperspaces associated with aerospace systems.

9.1. Framework Opportunities

In order to provide a balanced perspective of the ensuing contributions of this research, three key opportunities for extending this research are discussed hereafter, specifically of the Tradeoff Analysis Framework and Change Taxonomy. In addition to these, the unique usage of Principal Component Analysis to identify the complementary and competing nature of the system outputs in a tradeoff hyperspace is also discussed as a potential opportunity. While there are observed opportunities for extending the specific methods and framework from its application in the case studies employed in this research, these opportunities are contingent upon the specific applications and ensuing methods used in the framework and therefore are excluded in this discussion of the framework opportunities. The corresponding opportunities of interest are those at the macroscopic level, meaning that these opportunities are inherent to the Tradeoff Analysis Framework, Change Taxonomy, and methods independent of framework application.

9.1.1. Framework Applicability

The first opportunity to extend this research stems from the observation that the Tradeoff Analysis Framework is an example of a **prescriptive** methodology that characterizes how engineering design and evaluation *should be executed* based on observations of the design process being executed in practice. Therefore, the prescriptive framework provides a basic methodological structure with constituents that can be defined and tailored by a given designer or user of the framework, and thus the framework provides a convenient platform for analyzing engineering systems. However, the limitation of the framework is that it is a prescriptive and not descriptive framework. The latter type of framework is structured such that it characterizes how engineering design and evaluation *is executed* based on observations of the engineering design process executed in practice. In a descriptive framework, each component is fully defined for any

designer and user and is specific to the engineering process(es) used to develop the framework. The major difference between prescriptive and descriptive frameworks is therefore that the descriptive framework development and execution will differ for each user and application since it is built from scratch and specifically to the application of interest, whereas with a prescriptive framework, the underlying structure of the framework never changes and thus the only development and execution changes are specific to the methods used for each framework component [153]. Therefore, prescriptive frameworks are somewhat ideal representations of a process, but they are typically more general (abstract) and thus widely applicable than descriptive frameworks.

The resulting Tradeoff Analysis Framework thus suggests how tradeoff hyperspaces should be analyzed, but this may not be indicative of how a particular user or analyst of the framework desires to analyze such hyperspaces, for a particular application. Therefore, while the framework was developed to be as generalizable as possible, the tradeoff is that the framework has to be abstracted and representative of observed engineering design processes. As such, the analyst or user of the framework may find that departures from the framework are needed in order to conform to their particular intended application and these become potential opportunities to extend the framework development and further its applicability. The best evidence of this are the three Tradeoff Analysis Frameworks developed in this research, specifically the Framework with Multiple Stakeholders and the Framework with Optimization, which are departures from the Baseline Framework, which were developed in response to extending the Baseline Framework to analyze new types of tradeoff problems. Even though the framework provides a convenient structure for adaptations, it cannot prescribe how this is to be done, thus the opportunities to extend the framework may be abundant and developing such extensions is a creative process. For a specific example, consider the framework as it was modified in the third case study in order to account for uncertainty, which was an important aspect of understanding the impact of innovation in this particular application. Subsequently, the framework, specifically the system transform, was modified using a Monte Carlo Analysis (random sampler) to account for the uncertainty in the external factors (see Section 8.5.2). And while the underlying framework provided a convenient structure for making this modification, it did not prescribe how one must account for uncertainty in the framework.

Any prescriptive framework provides opportunities for further development and maturation based on the users of the framework. The concluding point about this observation is that the Tradeoff Analysis

160

Framework and subsequent versions of the framework provide a convenient starting point for analyzing tradeoff hyperspaces for engineering systems, but as demonstrated through the framework implementation insights in Sections 6.5.2, 7.5.2, and 8.5.2, each application of the framework will likely have to be tailored to the system/problem of interest and this may not be trivial. Therefore, because the framework is so generalized (prescriptive), it cannot be executed for a particular application without defining and developing the framework components and the required creativity and effort to do this should not be overlooked, and this is therein an important opportunity for the analyst or user of the Tradeoff Analysis Framework.

9.1.2. The Change Taxonomy

The second potential opportunity to extend this research and the Tradeoff Analysis Framework applicability arises from the Change Taxonomy used to structure the proposed changes in the applications of the framework in the case studies. Although the taxonomy was a central theme in the case studies, this opportunity is only realized when using the taxonomy to the structure the proposed changes in applying the Tradeoff Analysis Framework. Recall, that the purpose of the Change Taxonomy was to identify, and thereby structure the potential sources of change, or innovation in a given system to be analyzed by the framework. Subsequently, two dimensions of change in engineering systems were identified and used to create the Change Taxonomy and they are technological (technology) and operational (ConOps) change. The resulting four combinations of these two axes of change are No Change, singular (*i.e.,* uncoupled) change in technology *or* ConOps, and radical (*i.e.,* coupled) change in technology and ConOps. The perspective of change inherent to the Change Taxonomy is thus a product- or system-focused change, given the taxonomy's emphasis on changes in technology (hardware, configuration) and operations. Correspondingly, the manifestation of these changes in the Tradeoff Analysis Framework is the analysis of new system designs and operations and/or modifications to existing system designs and operations.

The previous, brief summary of the Change Taxonomy consequently substantiates one of its inherent limitations, which becomes an opportunity, namely, it does not holistically capture potential sources of change that can affect a system. While the Change Taxonomy does identify the two common sources of change in engineering systems, depending on the perspective of change adopted, there may be several sources or types of change that are not captured by the Change Taxonomy and these become opportunities to extend the taxonomy to be explored with the Tradeoff Analysis Framework. For example, one important source of change and thereby source of potential innovation is organizational change. Since any

161

system development is the responsibility of an underlying organization (or organizations), there is an important human element and subsequent interaction that can strongly influence the ultimate design and operation of a system and thereby its respective value. This, and other unique forms of change, or innovation may therefore need to be included in the Change
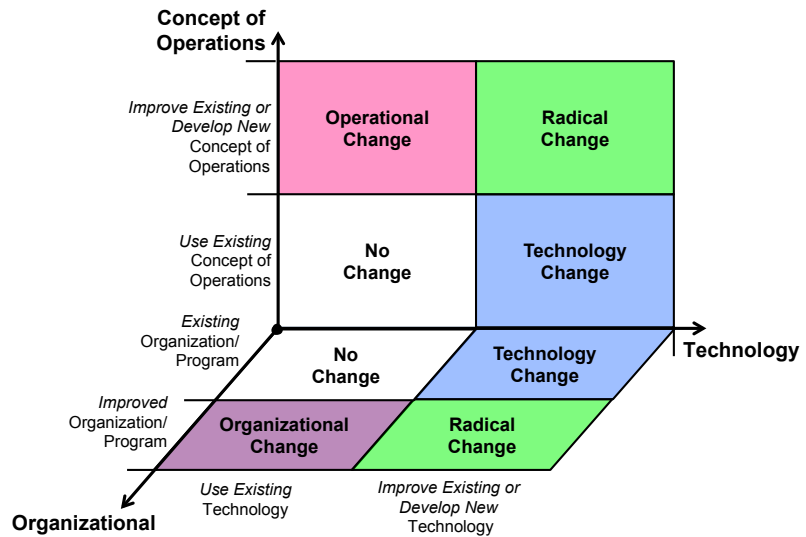
Figure 9-1. Three-Dimensional Change Taxonomy.

Taxonomy in order to be representative of the progression in a particular type of engineering system (and program). Conceptually Figure 9-1 shows the addition of a new, third axis of change, or innovation to the current Change Taxonomy using the previous example of organizational change as the newly added dimension to the taxonomy. As seen in Figure 9-1, there are now eight categories of change in the taxonomy, the most significant departure from No Change being coupled-coupled (*i.e.,* the combination of both types of Radical Change) change amongst technology, ConOps, and organizational change.

While the current Change Taxonomy may not holistically capture every source of potential change in an engineering system or program, the above example demonstrates that the underlying construct of the taxonomy is easily adaptable to fit a particular change, or innovation emphasis. Despite this, applying the Change Taxonomy as it was in the case studies of this research to analyze aerospace systems remains an important contribution of this research.

9.1.3. Analyzing the Tradeoff Hyperspaces with Principal Component Analysis

In two of the case studies in this research (refer to Sections 6 and 8), Principal Component Analysis (PCA) was used to quantify the competing and complementary nature of the system outputs constituting the tradeoff hyperspaces considered in the case studies. PCA can be used to map a multi-variate set of data to a single model where the model is a dimensionless representation of the data set derived from an Eigen-analysis of the data set; a detailed discussion of the PCA method can be found in Ref. [86]. As discussed in its application in Section 6.4.2 and 8.4.4, PCA can be used to represent a hyperspace of system output

162

tradeoffs in a reduced-order space, which provides a simplistic, or lower-order representation of the relative correlation, or tradeoffs amongst the outputs of interest in a hyperspace. PCA achieves this by mapping the system output space to a *n*-dimensional principal component space, where *n* may be less than the order of the original system output space. If this is the case, PCA effectively reduces the order of a tradeoff hyperspace. The particular manner in which PCA can be used to identify the complementary and competing nature of the system outputs is by representing the tradeoff dimensions in angular proximity to one another in a reduced-order space, given the space of system outputs analyzed with the Tradeoff Analysis Framework; in the PCA representation, the outputs increase in magnitude along their respective dimension. Specifically, as the angular offset between any two dimensions nears 0º, 90º, and 180º, the two outputs become perfectly complementary, neutral, and perfectly competing, respectively, *assuming* that an increasing magnitude in an output is more desirable. Complementary output dimensions are aligned such that increasing the value of one increases the value of the other, whereas competing dimensions (*i.e.,* tradeoffs) demonstrate the converse of this situation. And neutral output dimensions are uncorrelated, or independent. Refer to Sections 6.4.2 and 8.4.4 for examples of using PCA to identify the complementary and competing nature of system outputs in a tradeoff hyperspace.

The usage of PCA to quantify the relative complementary and competing nature of a set of system outputs can be extended by analogy to analyze the stakeholder valuation space. For example, if the uniform-additive cost-benefit preference structure (*i.e.,* "λ-Set") used in the first case study is assumed (refer to Sections 6.3.3 for a description of this preference structure), it is possible to analyze the collective value, or preference structure space of the stakeholders using PCA. If this is done, PCA can be used to identify the relative complementary and competing nature of the stakeholders' preferences. This type of analysis would lead to determining the correlation, or lack thereof, amongst stakeholder preferences and thereby areas of stakeholder alignment and misalignment amongst the stakeholders in terms of their respective preferences. This analysis will in turn may be useful for facilitating negotiations amongst stakeholders in the value, or preference domain (see Section 2.2.6), rather than in the system output space as was explored in the first and third case studies in this research when PCA was applied in combination with the Tradeoff Analysis Framework.

In its application in the first and third case studies, the correlations amongst the system outputs, as determined using PCA, were found to be highly sensitive to the assumed external factors, which described

163

the operating environments of the respective system considered in each of these case studies. Therefore, in order to gain an understanding of the robustness of the competing/complementary nature of the system outputs, it might be constructive to use the Tradeoff Analysis Framework to generate the system output space corresponding to a number of candidate external factors, or operating environments for a system and then to analyze them using PCA. For example, in the PCA analysis in the first case study, the observations about the system output tradeoffs were based on comparing the PCA analysis of the system outputs from two different days of weather. However, in order to generalize the system output tradeoff trends it might be worth comparing the PCA analysis of the system outputs generated from the framework corresponding to a year's worth of atmospheric cruise conditions, or weather. This would ultimately lead to a quantification of the volatility of the system output tradeoffs in a hyperspace as they depends on the assumed operating environment for the system, and this may be useful for providing a more comprehensive perspective of the important tradeoffs for a system, relative to its operating environment.

9.2. Contributions

Despite the aforementioned limitations of the research, given the scope of this research and the corresponding literature review in Sections 2 and 3, this research collectively makes a unique and independent contribution to the existing methodological literature on methods for evaluating the impact of change, or innovation in aerospace systems.

SUMMARY OF CONTRIBUTIONS

1. **A coupled change (innovation) assessment**

   This research developed a unique Change Taxonomy based on the technology forecasting and management literature to guide and characterize the change, or innovation investigations conducted in this research. The operational and technology dimensions of the Change Taxonomy, and the resulting coupled change, or innovation studies conducted in this research via the Tradeoff Analysis Framework are unique to the relevant literature on frameworks for evaluating the impact of change in the aerospace field.

2. **A framework for analyzing tradeoff hyperspaces**

   The framework developed in this research in order to evaluate the impact of changes in aerospace system design and operation (via the Change Taxonomy) identifies many key components important for analyzing the tradeoff hyperspaces associated with a system. The resulting Tradeoff

164

Analysis Framework developed in this research organizes these components into a coherent, repeatedly executable framework that has many attributes, which are discussed in the relevant sections throughout this document. As a whole, the Tradeoff Analysis Framework is unique to the methods and approaches offered in the literature, which are discussed in Sections 2 and 3.

3. **Accounting for value structures from multiple stakeholders**

   The cornerstone of the framework development and application is accounting for the preferences of multiple stakeholders, specifically through the use of valuation theory. These preferences are a crucial consideration for determining the best design and operation of a system, given the stakeholders of interest. In considering stakeholder preferences, the framework was subsequently used to identify stakeholder misalignment, which can lead to conflicts, and correspondingly facilitate stakeholder alignment, and both of these aspects of the framework usage are unique to the relevant literature.

4. **Framework Implementation Insights**

   The implementation insights gained through applying the Tradeoff Analysis Framework in the case studies are the fourth and remaining contribution of this research. This contribution is specifically manifested through the unique framework implementation insights gained through the previous applications of the framework in the case studies, which have ultimately started a dialogue on the attributes and potential usages of the framework that will hopefully be continued through future applications of the framework.

9.2.1. A Coupled Change (Innovation) Assessment

The first contribution of this research is the Change Taxonomy and as it was applied to analyzing the tradeoffs associated with change, or innovation in aerospace systems; this taxonomy is shown again in Figure 9-2 for convenience. Given the aerospace innovation literature discussed in Section 3, the Change Taxonomy represented in Figure 9-2 is unique, in terms of identifying distinct sources of change or innovation as well as the ensuing exploration of this taxonomy in the respective case studies of this research. The common trait amongst these literature sources is that they singularly evaluate the impact of Technology Change relative to No Change, which implies that the approaches they developed are to assess the impact of developing new technologies, or improving the performance of existing technologies (while considering the associated reliability of these technologies). But this ignores the other important dimensions of innovation,

namely, Radical Change, which is a coupling of Technology and ConOps innovation and is an important aspect of the evaluation of innovation for many systems.

In response to the observed change, or innovation examined in the literature and given the Change Taxonomy, this research and the ensuing Tradeoff Analysis Framework, which is the second major contribution of this work (see Section 9.2.2), explored both instances of singular (decoupled) and coupled change, or innovation. The resulting categories of change analyzed in the case studies performed in this research are summarized in Figure 9-3. In the aircraft cruise operations case study only singular change along the

Figure 9-2. Change Taxonomy.

Figure 9-3. Changes Explored in the Case Studies.

ConOps axis was explored (Case Study 1, Section 6). In the aircraft approach procedures case study (Case Study 2, Section 7), the emphasis was on evaluating Radical Change as enabled through new aircraft technology, which in turn allowed for the design of new aircraft approach procedures. And, lastly, in the remote sensing spacecraft case study (Case Study 3, Section 8), singular change was examined along the Technology and ConOps axis, specifically with fractionated spacecraft using the On-Demand operational scheme and monolithic spacecraft using the Predicted operational scheme, respectively. Then, coupled change was analyzed in this case study to assess the impact of fractionated spacecraft using advanced operational schemes. Given the types of change, or innovation collectively evaluated in the case studies, the entire Change Taxonomy was therefore explored in this research.
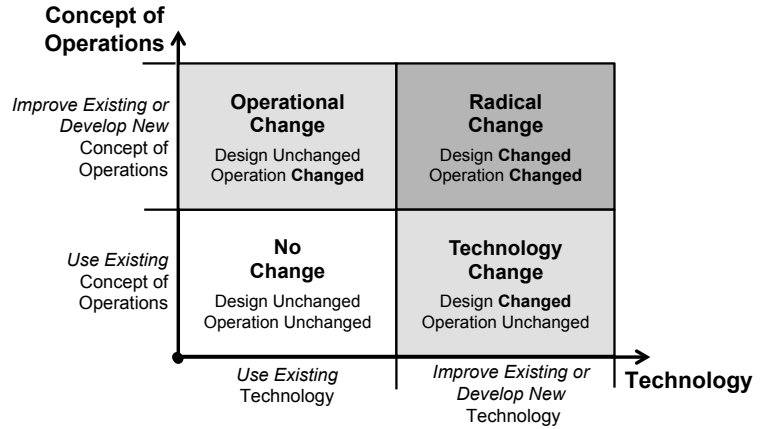
166

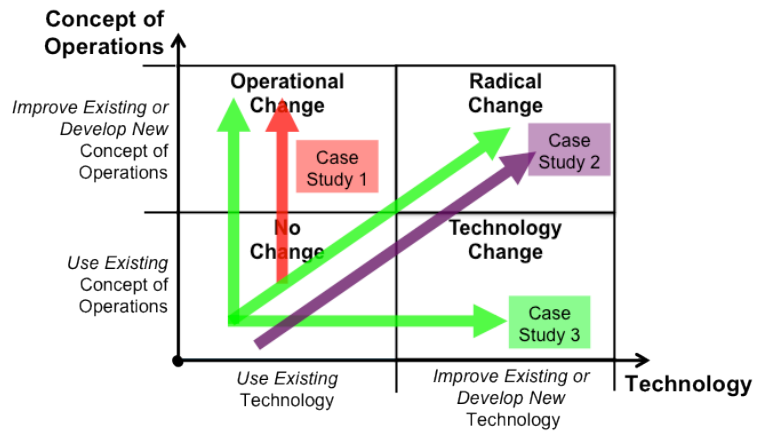The remaining contribution stemming from the ensuing coupled change assessments in this research, which explore the Change Taxonomy, is their departure from a metric-centric approach for identifying and evaluating change, or innovation. The approaches in the relevant literature (see Section 3) predominantly rely on methods for assessing the impact of innovation centered upon a critical metric, or measure of success; for example, using the TRL scale to measure the success of innovation. This *a priori* focus on a measure of success can bias the ensuing identification of innovation through conforming the sources of innovation to the metric(s) chosen to measure how successful innovation is. The coupled change and innovation emphasis adopted in this research, and corresponding Change Taxonomy developed, identifies potential sources of change or innovation without any premise, which would include the metric(s) by which the impact of change, innovation will be measured. While a seemingly subtle contribution, in terms of generality, keeping the basis for change or innovation independent of a specific system (to be analyzed) or measures of success ultimately makes the Change Taxonomy more broadly applicable.

9.2.2. A Framework for Analyzing Tradeoff Hyperspaces

The Tradeoff Analysis Framework is the second major contribution of this research, which is shown again in Figure 9-4 for convenience. The framework was specifically developed through identifying crucial components that lead to the creation of tradeoff hyperspaces for aerospace systems and that are, hopefully, required to resolve these hyperspaces. As discussed in
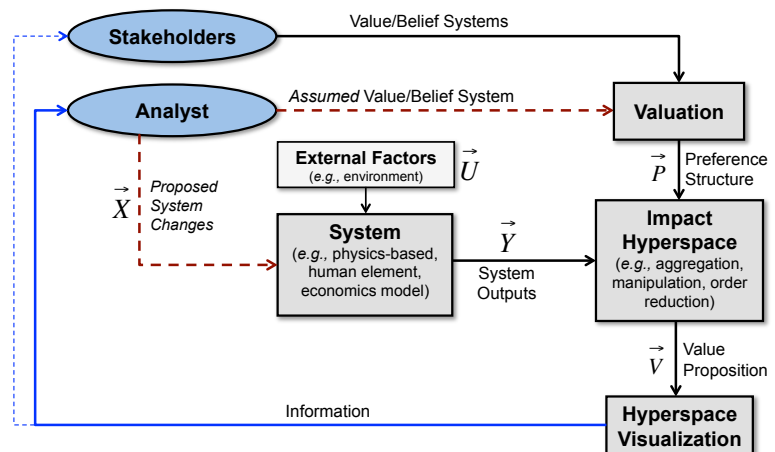
Figure 9-4. Framework with Multiple Stakeholders.

detail in Section 4, the major framework constituents include the analyst and stakeholders, system and external factors, valuation, the impact hyperspace, and visualization. And each of these components is connected directly, or indirectly via a flow of information. This framework therefore addresses the first objective of the research, which is to "develop a framework to analyze tradeoff hyperspaces" and provides a much more holistic perspective of the various factors that affect the value (impact) of change or innovation in systems than demonstrated in the relevant innovation framework literature (see Section 3). There are a few immediate departures of this framework from those offered in this literature to assess the impact of innovation and each of these will be discussed in turn.

167

First, the Tradeoff Analysis Framework can be used to categorize and ultimately analyze potential types of change, or innovation through the proposed changes to the system in the framework. As discussed in the previous section (Section 9.2.1), this approach to change, or innovation identification and subsequent analysis is unique to the literature. While the proposed changes were structured through the types of change in the Change Taxonomy for the case studies performed in this research, it is important to note that the framework is not constrained to structuring proposed system changes as types of change and instead may be tailored to any system and investigation of interest, there further increasing its potential applicability.

The second inherent departure of the framework from those offered in the literature is that it is not constrained to assessing the impact of a system using one (or very few), performance-based, metrics such as "technology readiness" or "technology maturity." While these metrics may be appropriate choices for some applications, this negates the original motivation of this research, which is established through recognizing the increasing importance of considering the multiple *tradeoffs* associated with the design and/or operation of aerospace systems. Therefore, an approach hoping to realistically analyze the impact of a system's respective design and operation should account for multiple (sometimes numerous) important system objectives.

The concluding observation made in the previous paragraph uncovers the third major departure of the Tradeoff Analysis framework from the approaches offered in the literature, which is generalization. Within the context of innovation frameworks in the aerospace domain, providing general approaches to perform such analyses as this research does through the Tradeoff Analysis Framework has several key benefits. First, in many analyses it is desirable to run experiments and compare and contrast the results from the studies. A general framework that provides a clear, repeatable process can help keep experiments unbiased relative to the means of obtaining the experimental results. Without having an underlying structure to guide the evaluation of a system, it is easy to make assumptions or add factors to the evaluation process, thereby compromising the equity of the results. Despite the benefits of providing general frameworks, for those approaches in the literature that intended on being generalizable, thus aligning themselves with the objective in this research to provide a general framework for analyzing tradeoff hyperspaces, they are overly constraining in terms of implementation. To start, and as mentioned previously, many of the "general"

frameworks in the literature already define the metrics to be used to measure the impact of a system. Second, all of the frameworks, generalizable or not, are entirely focused on quantifying the impact of technological change, thus already constraining their usage along this axis of change. As evidenced by their cited application(s), the frameworks in the literature have either never been applied or applied to a very specific system and innovation assessment problem. Thus the approaches in the literature are useful for the particular application(s) they examine, but they offer limited utility from the perspective of this research.

The general applicability of the framework developed in this research is best evidenced by: (1) the retroactive, conceptual framework applications to the historical case studies (Section 4.2.2) and (2) the detailed application of the framework to three appreciably different case studies in the aerospace domain (see Sections 5-7). Ultimately, through identifying important considerations in analyzing tradeoff hyperspaces, the Tradeoff Analysis Framework expands the breadth of influences to be considered in performing such analyses. Frameworks, especially those constrained to evaluating the impact of *Technology Innovation*, tend to focus entirely on the system transform in the Tradeoff Analysis Framework, where in reality the problem of analyzing tradeoffs is much larger; Figure 9-5 positions the limited scope of the frameworks offered in the literature (and their subsequent developmental emphases) in the context of the Tradeoff Analysis Framework. Therefore, while, the Tradeoff Analysis Framework is not all encompassing, it provides additional perspectives that ultimately broaden the view and subsequent understanding of the innovation evaluation problem.
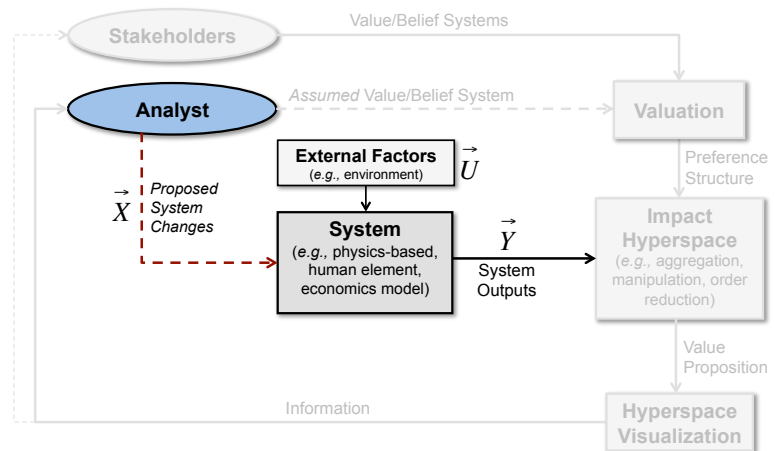
Figure 9-5. Constrained Framework Scope.

Another attribute of the framework is extensibility. As a complement to the generalizable nature of the Tradeoff Analysis Framework, the ability to adapt and extend the framework to a particular application is valuable. As previously mentioned, the Tradeoff Analysis Framework developed and applied herein implicitly recognizes that it is not an "end-all" framework for analyzing the tradeoffs associated with the

design and operation of a system. Thus, the framework allows for adaptations and additions to be made to it as seen fit for a particular application. This extensible nature of the framework was first demonstrated through its respective development, specifically through the three versions of the framework, the: Baseline Framework, Framework with Multiple Stakeholders, and Framework with Optimization. Additionally, the extensibility and adaptability of the framework was demonstrated through the application of the framework in the three case studies (see Sections 6-8). Subsequently, there have been many versions of the framework explored in this research and each subsequent version leverages the implementation insights gained from the other framework versions to adapt the framework to the particular application of interest, thereby contributing to the overall utility of the Tradeoff Analysis Framework.

The remaining attribute of the framework is its simplistic representation. The simplistic nature of the framework is a derivative of its level of abstraction and, while each framework constituent may be complex to develop and execute, conceptually, the framework is straightforward to understand and discuss. One advantage of breaking down a potentially complex problem into simple "blocks" and information flows is that it can facilitate the framework development and subsequent application. For example, through parsing out the various major components in analyzing tradeoff hyperspaces, the framework development can take on many forms, including the simultaneous development of various constituents, a series development of the constituents, or hybrid schemes. In large engineering programs where there are often teams of engineers working on a project, having this conceptual framework to communicate the combined effort amongst the team and, more importantly, to the relevant stakeholders may be invaluable. From this perspective, the framework can be thought of more as a communication platform than an analysis tool.

9.2.3. Accounting for the Preferences of Multiple Stakeholders

The third contribution of this research is explicitly accounting for the preferences of multiple stakeholders and incorporating these preferences as part of evaluation criteria in the framework. In doing this, the second objective of this research is met, namely, "account for value structures from multiple stakeholders." Accounting for the preferences of these stakeholders is paramount to implementing the framework and evaluating the ensuing results in the context of stakeholder value. Given a set of stakeholders and their implicit preferences as to the best balance amongst the system output tradeoffs of interest, there are many approaches for incorporating their preferences in the framework. One approach is to use valuation theory; this is presently the approach considered in the Tradeoff Analysis Framework, specifically for the valuation framework constituent. However, this is not the only means for incorporating stakeholder preferences in

170

the framework and, thus, using valuation theory in the framework may be viewed as a present limitation of the framework, provided more preferable methods for incorporating stakeholder preferences exist.

Since stakeholders are often responsible for making decisions about the system's respective design and operation, the stakeholder and valuation component of the framework is a crucial and a new addition relative to those frameworks offered in the literature for analyzing the impact of innovation or change in engineering systems. This thereby demonstrates a unique attribute of the Tradeoff Analysis Framework, which is a broadened (*i.e.,* beyond technical) consideration of the various influences and factors affecting the analysis of tradeoff hyperspaces. The systemic issue that may arise from incorporating multiple stakeholder value structures is potential stakeholder misalignment. This research suggests the use of valuation theory to identify this misalignment and then the use of several complementary approaches for facilitating stakeholder alignment.

9.2.4. Framework Implementation Insights

In order to evaluate the applicability of the Tradeoff Analysis Framework, three case studies were employed; these studies and their key findings are summarized in Sections 6.5.1, 7.5.1, and 8.5.1 and these findings form one contribution this research. However, another source of important contributions in this research are the framework implementation insights, which were gained from applying the framework in the case studies. These implementation insights are justified as major contributions of this research because they ultimately improve the Tradeoff Analysis Framework, regardless of the framework application, and because in the context of the relevant literature on developing frameworks for evaluating aerospace systems, none of these sources discusses the important issues/considerations raised through these insights. These framework implementation insights also serve the purpose of providing appropriate closure to the case studies investigated in this research. The key framework implementation insights gained in this research are summarized hereafter and discussed in full in the appropriate case study sections as cited.

CASE STUDY 1 — SINGLE STAKEHOLDER, AIRCRAFT CRUISE OPERATIONS (SECTION 6.5.2)

The framework implementation insights resulting from this case study include:

- Using the framework as a policy analysis mechanism
- Using the framework to infer stakeholder preferences
- Representing (visualizing) the system outputs and value propositions

CASE STUDY 2 – MULTI-STAKEHOLDER, AIRCRAFT APPROACH PROCEDURES (SECTION 7.5.2)

The framework implementation insights resulting from this case study include:

- Using the framework to identify stakeholder misalignment

- Using the framework to facilitate stakeholder alignment

- The complementary usage of different framework versions

CASE STUDY 3 – MULTI-STAKEHOLDER, REMOTE SENSING SPACE MISSION (SECTION 8.5.2)

The framework implementation insights resulting from this case study include:

- Addressing uncertainty in the framework

- Making modifications to the framework

- Representing (visualizing) uncertainty in the system outputs and value propositions

9.3. Scope of Framework Applicability

The Tradeoff Analysis Framework is of potential use for analyzing a variety of tradeoff problems, provided they can be characterized through the framework components. Given the system-agnostic nature of the framework, it also provides a uniform basis for comparing and contrasting different tradeoff analyses. As shown through the case studies conducted herein, the framework can be used to analyze appreciably different systems. In terms of why the framework should be used, this is established in Section 1 through the research motivation, specifically, that the framework offers opportunities to understand and ultimately analyze important tradeoff hyperspaces associated with a system's respective design and/or operation. It is worth noting that the framework does not have to be used to analyze a tangible system, for example, the framework can be used to analyze the tradeoffs associated with an organization.

The ultimate key to knowing whether or not the framework is applicable is whether or not the problem of interest can be characterized through the framework components, with or without modifications to the framework that do not affect its underlying functionality (this is discussed in more detail in Section 8.5.2). If departures from this underlying functionality are required to analyze a system, then technically the framework is not applicable to that problem, however, the framework may still be of use as a basis for creating a new version of the framework to analyze that problem. From a system/problem-agnostic perspective, this is exactly why the Framework with Multiple Stakeholders (Figure 4-2) and the Framework

172

with Optimization (Figure 4-3) were created and are treated as different versions of the Baseline Framework, each with their emphasis on performing a certain kind of tradeoff analysis.

Given the breadth of potential framework applications, it might be applicable at any point during the engineering design/evaluation process, beginning with the early concept studies, to retroactively analyzing a system following the end of its respective operation. Thus, given the notional design process shown in Figure 9-6, the Tradeoff Analysis Framework might be applicable during any of the stages shown in this figure. This is evidenced within this research, specifically the three case studies used to evaluate the
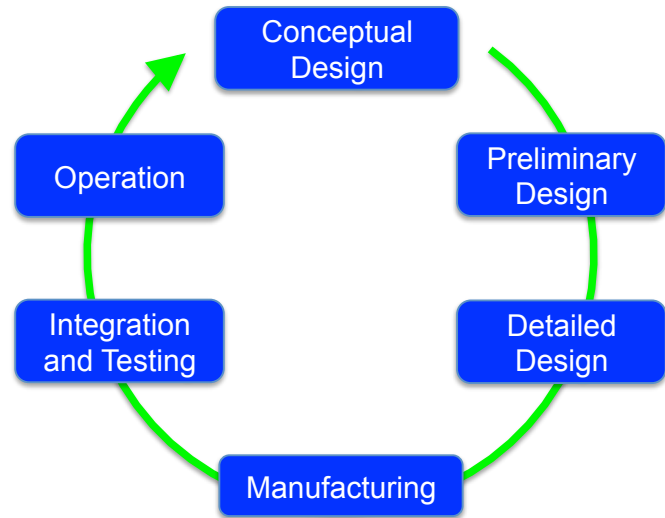
Figure 9-6. A Notional Design Process.

framework applicability, which demonstrate this breadth of applicability during the design process. In the first and second case studies, the framework is used to analyze the tradeoffs associated with currently operational aircraft; hence, the framework is being applied in the operational phase of the design process. Conversely, the third case study (Section 8) analyzes the tradeoffs associated with a hypothetical spacecraft, thus the framework is being applied during the conceptual design stage. Thus, in summary, the Tradeoff Analysis Framework may likely be applicable at any point during the design process. With this said, research is required to fully substantiate this claim through further testing of the framework applicability on systems with different levels of maturity.

173

10. CONCLUSION

This research was motivated by to need to analyze tradeoff hyperspace problems associated with the design and operation of aerospace systems. Tradeoff hyperspaces are created through internal tradeoffs amongst the objectives of interest for a system, for example, reducing fuel burn at the cost of increasing flight time in the case of an aircraft. In addition to system tradeoffs there may be multiple stakeholders of interest to the system and each may have different preferences as to the best balance amongst the tradeoffs. Consequently, the combination of different, or competing stakeholder preferences and tradeoff hyperspaces makes the process of determining the best, that is, most stakeholder amenable, design and operation of a system more challenging. In response to this, the corresponding objectives of this research were to develop a framework to analyze tradeoff hyperspaces and to account for the preferences of multiple stakeholders.

The Tradeoff Analysis Framework developed in this research to analyze tradeoff hyperspaces is the focal contribution of the research. The major advantage of the framework is that it is a useful tool for analyzing real tradeoff problems in engineering and it also provides a common basis for discussing how complex tradeoff problems in engineering can be understood and subsequently analyzed. The framework applicability was evaluated through using it to analyze three different relevant tradeoff problems in the aerospace field. These applications focused on using the framework to assess the impact of changes, or innovation in aerospace system design and operation. The framework applications grew in complexity in terms of both the challenges of applying the framework as well as the type and magnitude of proposed changes to the system that were subsequently analyzed. The first, second, and third case studies specifically analyzed the impact of change (or innovation where applicable) for aircraft cruise operations, aircraft approach procedures, and remote sensing space missions, respectively. The case studies also demonstrate the framework usage and applicability at different stages of engineering program lifecycles. The first two case studies assessed the impact of changes to *existing* systems (*i.e.,* fully operational aircraft) whereas the third case study assessed the impact of changes to *new*, hypothetical spacecraft concepts (*i.e.,* a spacecraft currently under development) called fractionated spacecraft. Valuable insights were subsequently gained from the applications of the framework in the case studies regarding the tradeoffs and value associated with change or innovation in the respective system of interest in the studies; a summary of these key insights is presented hereafter.

175

The application of the Tradeoff Analysis Framework yielded insights about the framework's applicability to analyze tradeoff problems in engineering. The first key insight was with regard to exploring how the framework can be used to represent, or visualize tradeoff hyperspaces. This element of the framework is crucial as it provides the key information to be fed back to analyst and stakeholders in order for them to make educated decisions about the design and operation of a system. With regard to visualization it was found that there are numerous techniques for visualizing large volumes of information but the three fundamental dimensions that can be used to represent data effectively limit these techniques. In response, Principal Component Analysis (PCA) was used with the framework to combat this limitation and lead to an ability to represent high-order (*i.e.,* 3+ dimensional) tradeoff hyperspaces with a lower order (*e.g.,* a two-dimensional) representation. In two of the case studies performed in this research, the PCA representation readily showed the most important tradeoffs in two dimensions, for example, rather than in the original six dimensions constituting the tradeoff hyperspace in the first case study regarding aircraft cruise operations. These representations were then conveyed back to the analyst and stakeholders in order for them to make informed decisions about the design and operation of a system on the basis of needing to resolve the most important system tradeoffs.

The second key framework implementation insight was exploring the potential uses of the valuation component of the framework, which is important since it provides to necessary mechanism to incorporate stakeholder preferences as part of the criteria to evaluate candidate designs and/or operations of a system. In this research, the valuation framework component was specifically used to: identify stakeholder misalignment in terms of their respective preferences; facilitate stakeholder alignment in order to find a stakeholder-wide amenable design and operation of a system; to explore stakeholder behavioral responses to a hypothetical tax on certain system outputs; and to infer stakeholder preferences if they cannot elicit them. In the second case study regarding the design of new aircraft approach procedures into Boston-Logan airport, it was found that valuation can be used to identify stakeholder misalignment using the preference structures of the three stakeholders of interest: airlines, airports, and communities. In particular, there was a major source of misalignment between the community's and airline's/airport's preferences since the community directly bears the cost of aircraft noise but does not directly benefit from the operation of aircraft, which the latter two stakeholder do directly benefit from. After identifying stakeholder misalignment in this case study, a method for designing new procedures based on facilitating stakeholder alignment in order to address this misalignment was developed, which lead to development and subsequent

176

use of a valuation-based approach for optimizing the design of new approaches, which ultimately led to the successful design of a new approach route into Boston that balanced the preferences of all of the stakeholders. The second exploration of the usage of valuation within the framework was in the first case study where it was used as a policy analysis mechanism, specifically to explore an airline's behavioral response, as measured by their perceived value-optimal cruise trajectory, to a hypothetical tax on producing contrails as well as direct operating costs. Specifically, this usage of valuation contributed to learning about how valuation can be used to explore the relationship between value-based incentive mechanisms and the preferred design and operation of a system from a stakeholder's perspective. Lastly, in the first case study, valuation was used to infer stakeholder preferences for the system outputs if they cannot elicit them for some reason. Situations when this may occur are if stakeholders are unsure of their preferences for certain system outputs in the tradeoff hyperspace. The subsequent use of valuation within the framework in this particular analysis lead to the inference of an airline's possible preferences for the cost of flight time and fuel, assuming the hypothetical situation they were unsure of their preferences for these outputs. Thus, unique insights about ways to use valuation to address stakeholder preference uncertainty were developed in this last exploration of the valuation component in the framework.

The third key framework implementation insight was derived from exploring modifications to the framework in order to use it to analyze specific tradeoff problems. This aspect of learning about the framework applicability was important because each of the framework components offers opportunities for the analyst in the framework to develop and apply unique methods to fit the framework to a particular application. One example of this was in the second case study performed in this research where the framework was modified and used to conduct a design of experiments approach to design new aircraft approach procedures into airports. This modification specifically lead to the use the framework version with optimization to explore the space of potential routes around an airport and therein determine the most valuable route to analyze in detail. Another example of modifications made to the framework was in the third case study where the framework was modified in order to address significant uncertainty in the system outputs and therein stakeholder value introduced from uncertain external factors (*i.e.,* operating environments) for a remote sensing spacecraft. Specifically, a Monte Carlo Analysis was adapted to the framework in order to capture this uncertainty. Many other modifications to the Tradeoff Analysis Framework were made throughout the case studies in order to use it to perform certain types of analyses, and it is important to reflect on these as this provides to most direct contribution of knowledge about how

177

the framework can be extended to fit a particular type of application, which may in turn be useful for other similar framework applications.

While the Tradeoff Analysis Framework application in the case studies offered detailed insights about the specific systems analyzed in the studies, the aforementioned summary of insights with regard to implementing the framework in the case studies yield the methodological contributions of this research. In particular, this is because the implementation insights offered opportunities to learn about the potential breadth and depth of framework applicability and ultimately contribute to its development and maturity for future applications. As previously discussed, each of the insights was gained through testing the framework's applicability in the case studies and demonstrates the importance of learning about the framework through application. Applying the framework to real tradeoff problems in engineering is the most abundant source of feedback to further improve the framework and explore its continued functionality. And this feedback ultimately makes a meaningful contribution to the dialogue on analyzing, and subsequently gaining insights into, real tradeoff problems in aerospace engineering. While the case studies applied in this research yielded the first contributions to this feedback and dialogue, future uses of the framework will yield additional insights to contribute to the development and ultimate improvement of it. Specific recommendations for future work are discussed next.

One of the key areas for future work is to further explore situations when there are competing stakeholder preferences and to subsequently work on developing and applying methods for facilitating stakeholder consensus. Engineering tradeoff problems often involve multiple stakeholders who have different preferences with regard to the balance amongst the system objectives, or tradeoff dimensions of interest. If these situations occur, it increases the challenges associated with determining the "best" design and operation of a system. The Tradeoff Analysis Framework was used in the case studies performed in this research to explore methods for facilitating stakeholder consensus, in particular visualization approaches. The visualization component can help facilitate stakeholder consensus through identifying the key system output tradeoffs, which can educate stakeholders about the key tradeoff dimensions that need to be negotiated in order to decide on the design and operation of a system, given a set of candidate system designs and operations. While several visualization methods were explored to facilitate stakeholder consensus, this remains an active area of research and development in terms of the Tradeoff Analysis Framework.

The second key area for future research is further exploring the valuation component of the framework, as this remains the crucial mechanism for incorporating stakeholder preferences as part of the evaluation criteria for candidate system designs and operations. In the case studies performed in this research, a value function, specifically a uniform-additive cost-benefit function, was used to aggregate all of the system outputs into one metric of value via a preference structure called a λ-Set, which mapped the system outputs to value using stakeholder preference structures. While the analyses in the case studies did explore candidate designs and operations of a system relative to the tradeoff hyperspace dimensions created from the multiple system output of interest, ultimately at the end of each case studies the candidate designs and operations of the systems of interest were evaluated and then compared on the basis of value. However, it is important to recognize that there may be situations when it is not possible, or desirable to use a value function to aggregate all of the system output tradeoff dimensions into one value metric. Thus, an area for future research might be to explore the framework to analyze tradeoff problems when the evaluation criteria remains multi-dimensional for each stakeholder, which may consist of a set of system outputs that are partially combined into one value metric, but there remains several outputs that are not included in the value function. In addition to this recommendation, future work might also examine the usage of different valuation approaches to analyze tradeoffs. In the case studies performed in this research, cost-benefit analysis was used in one form or another as the value structure in the framework, but this is only one of many potential types of valuation methods, or approaches that may be applicable for providing a structure to capture stakeholder preferences. For example, future research in this area could explore the use of more complex valuation structures that may be better suited to value system outputs that are subjective such as the benefit that an airport derives from minimizing passenger delays. Alternatively, future work might analyze the sensitivity of uncertain value structures or functions to the proposed changes, or evaluate the impact of non-linear valuation on the resulting tradeoff insights gained from applying the framework.

The remaining recommendation for future work is to continue to apply the Tradeoff Analysis Framework to analyze other tradeoff problems than those analyzed in this research. Through this research, the framework was found to be useful for analyzing real tradeoff problems in engineering, and while the framework is still under development, it may benefit the analysis of other important tradeoff problems. For example, it might be of interest to use the framework to analyze systems with different maturity levels, thus exploring new and different stages of typical engineering program lifecycles where the framework may

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be of use. Alternatively, it might be useful to examine tradeoff problems where there are a large number of stakeholders as this may make the framework implementation notably more challenging in terms of capturing stakeholder preferences and facilitating alignment amongst the stakeholders, given the system and tradeoff dimensions of interest. Ultimately, future applications of the Tradeoff Analysis Framework not only provide a benefit to the problems being analyzed but they also provide the richest area for learning about the key attributes of the framework and its potential applicability, in the context of tradeoff hyperspace problems in engineering.

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APPENDIX A: HYPERSPACE VISUALIZATION (EXTENDED DISCUSSION)

The hyperspace visualization is a critical aspect of the framework because it is the mechanism for communicating the value proposition (or impact) of a proposed change to the analyst and stakeholders. There are numerous visualization methods and software packages available that can be used for the hyperspace visualization. A subset of these approaches and packages will be discussed hereafter, starting with an overview of fundamental visualization methods followed with a discussion of open-source software packages developed to visualize multi-dimensional information/data.

The fundamental visualization methods are parsed into two categories: patterns and detailed. A summary of these methods is provided in Table A-1 along with the maximum number of dimensions that can be practically visualized with the method. Note that the "Miller's Limit" is in reference to Miller's Cognition Limitation Rule, which states that people (*e.g.,* stakeholders) are limited to simultaneously trading (managing) in 7 +/- 2

	Visualization Method	Maximum Visualization Dimensions
Patterns	Icons	Miller's Limit (1-9)
	Glyphs	
	Parallel Coordinates	
Detailed	4D	4
	Slices	2+
	Plot-in-Plot	4+
	Carpet	Miller's Limit (1-9)
	Worlds-within-Worlds	
	Hyperslices	

Table A-1. Summary of Visualization Methods.

dimensions [151]. So, although methods subject to Miller's limit are suggested as having a maximum *practical* visualization limit of nine dimensions, technically the number of dimensions that can be visualized is unlimited.

AN IMPORTANT CONSIDERATION – THE OUTPUT AND DESIGN SPACE

The ensuing discussion of hyperspace visualization methods focuses on visualizing the system output and value proposition space, however, in terms of framework implementation it may also be useful to visualize the design space (*i.e.,* the proposed change/system representation space). Given that visualizing a proposed change (*i.e.,* the design space) is particular to the specific system and application of the framework, the hyperspace visualization described hereafter does not explicitly address visualizing the design space, although some of the visualizing methods discussed hereafter may be helpful in achieving this.

VISUALIZATION TYPE 1: PATTERNS

Pattern visualization methods rely on shape recognition to synthesize and ultimately represent multivariate data. Thus, these methods often abstract specific data details for the sake of providing a means to quickly

191

determine broad trends across the data. The commonality amongst pattern plots is representing data of different dimensions (or units) in the same plot by effectively normalizing each metric so that differences across the data can be compared, albeit not absolutely. Three pattern plotting methods are discussed hereafter: Icons, Glyphs, and Parallel Coordinate Plots.

- **Icons**

Icon plots abstract data by mapping it to a series of recognizable shapes (and colors). Once a data set is mapped to a set of icons, a macroscopic view of the data often readily identifies trends amongst the data (or variables). A simple example of an icon plot is shown in Figure A-1. Here, each 3x3 square represents the 9 outputs of interest for an aircraft cruise operation. Each entry is colored according to how large the output metric is in magnitude relative to the range of observed values for that metric. So, for example, a red shaded square indicates that a metric is the highest possible for that metric (100%) and, as the square shades near blue and purple, they reach the lowest observed value for a given metric (0%).
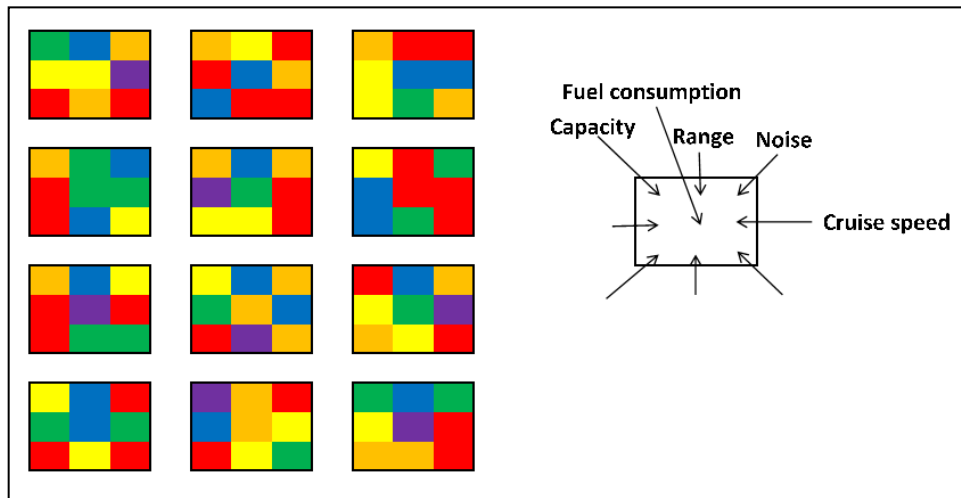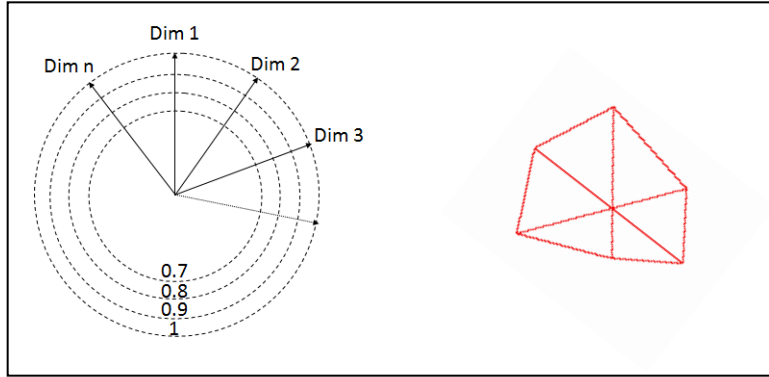

**Figure A-1.** Example of an Icon Plot.

- **Glyphs**

Glyph plots represent a set of data as a series of concentric rings at an angular offset of $2\pi/n$, where n is the number of independent data dimensions. Similar to the previous icon plot example, the data are plotted by normalizing them on the range of observed values for each data dimension (or metric). As the concentric rings increase in diameter, it represents an increasing normalized metric value. The construction of a glyph plot is summarized in Figure A-2 along with an example of glyph plot for an arbitrary six-dimensional data set.

192

Figure A-2. Constructing a Glyph Plot.

A collection of Glyph plots can be use to create a pattern plot, thus showing trends in the data on a macroscopic scale just as icon plots do. An example of this is provided in   Figure A-3.
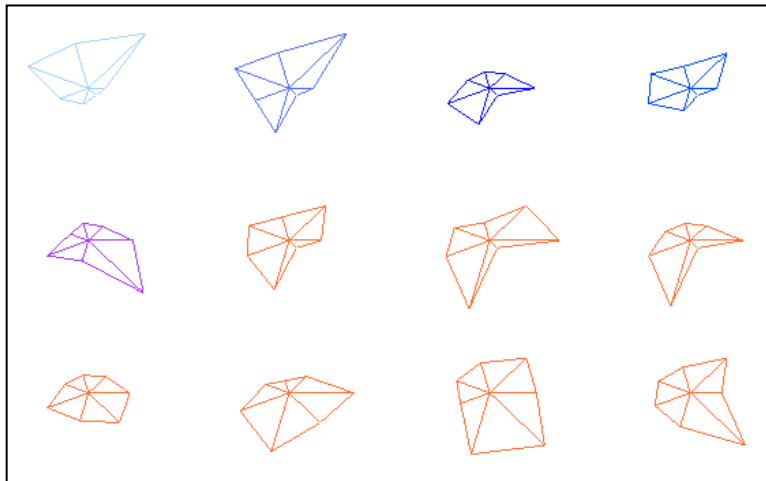
Figure A-3. Example of a Pattern Glyph Plot.

- **Parallel Coordinates**

    Parallel coordinate plots allocate data to a set of vertical scales or bars where each bar is dedicated to one data dimension or metric. The height of each bar is held constant and the range of the bar is that of the minimum and maximum observed values for a given metric. Each entry contributing to the data set is then plotted as one dot along these bars and then the dots are connected, thus creating a polyline. The result of plotting a large data set is a series of polylines that show general trends in the data amongst the metrics considered. An example of a five-variable parallel coordinate plot is provided in   Figure A-4.
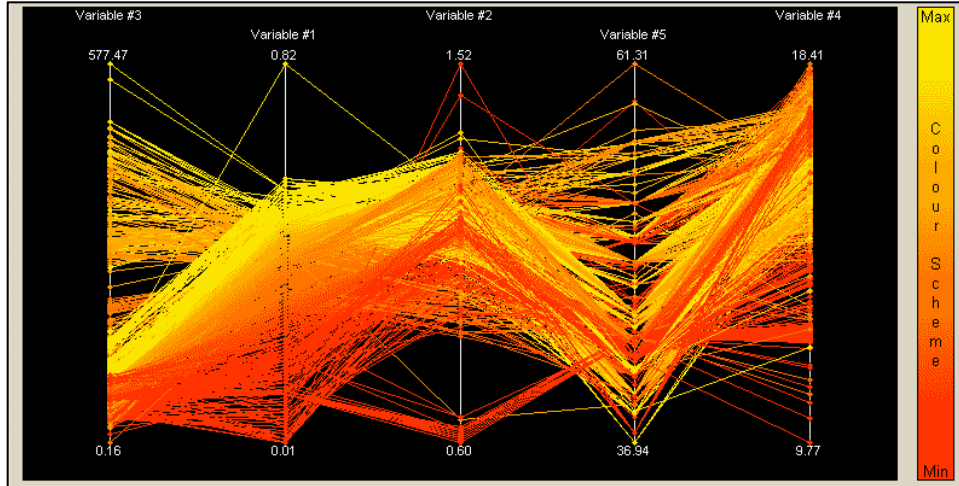
Figure A-4. Example of a Parallel Coordinate Plot.
(Source: Centre for Process Analytics and Control Technology)

VISUALIZATION TYPE 2: DETAILED

Unlike pattern plots, detailed plots represent multivariate data such that it is not normalized and thus kept in absolute units. The advantage of detailed plots is therefore that absolute comparisons and trends in data can be made, however, the disadvantage is that without normalizing the data, it limits the number of dimensions that can be effectively visualized. Six different detailed plots are presented hereafter and they include: 4D, slices, plot-in-plot, carpet, worlds-within-worlds, and hyperslices.

- **4D**

  4D plots are the most straightforward multi-dimensional detailed plotting technique. This visualization method plots data in three dimensions and then maps the fourth dimension of data to a color scale. An example of this visualization technique is provided in Figure A-5, which shows a 4D plot corresponding to an analysis of spacecraft architectures conducted by the author being evaluated with the metrics of lifetime (x), orbit altitude (y), revenue (z), and cost (color shading).
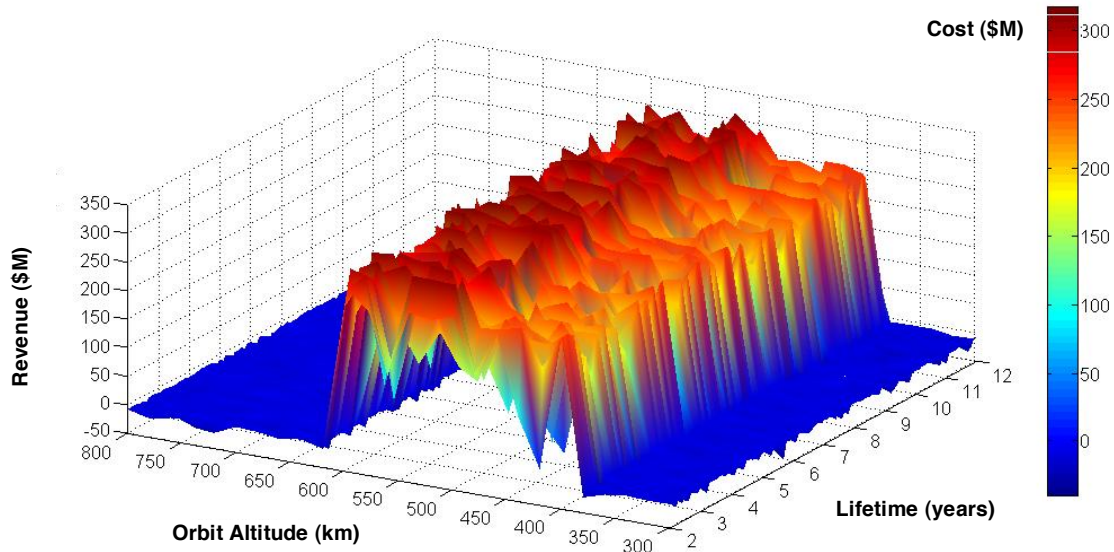
194

Figure A-5. Example of a 4D Plot.

- **Slices (2D)**

  Slices are two-dimensional cross-sections of a three-dimensional plot. Slices effectively dissect three dimensions of information into a series of two-dimensional planes. Thus, Slices are particularly useful for analyzing three-dimensional surfaces with complex curvatures since these types of surfaces often obscure trends in the data when viewed in three dimensions. A good example of this is the Matlab *peaks* function shown in Figure A-6 where, for example, it may be difficult to know the exact Z-axis value along the range of Y-axis values, given a specific X-axis value. For example, Figure A-6 shows a 2D slice of the Matlab *peaks* function at X = 0.
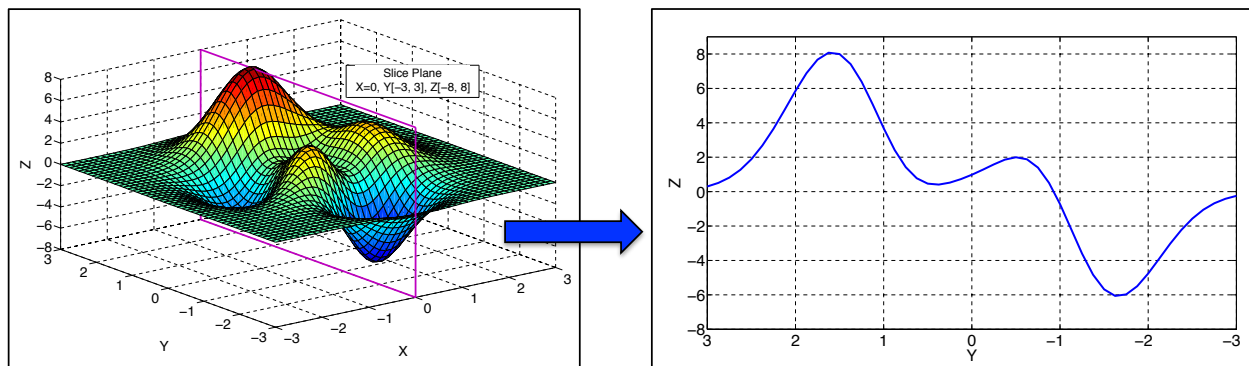

Figure A-6. Matlab *Peaks* Function with a 2D slice at X = 0.

195

- **Plot-in-Plot**

Plot-in-plot is a method for capturing multiple dimensions of information in either a two or three-dimensional plot. This method is a type of active visualization (as opposed to passive in the case of a 4D plot) where, given a point of interest in a two or three-dimensional plot, further information regarding that point is then called up and displayed. This type of plotting is useful when a given data point contains layers of information, for example, each data point is an aggregate statistic such as the median of a distribution of values. In this case, it may be useful to understand the distribution of values behind each plotted data point and this can be achieved with plot-in-plot methods, where the selection of a given data point automatically produces the corresponding distribution of data values. An example of this is shown in Figure A-7. In Figure A-7, the vertical axis displays the median lifecycle cost of spacecraft architectures versus spacecraft performance. While performance is constant, the median lifecycle cost is taken from a distribution of potential lifecycle cost values generated by a Monte Carlo Analysis. In this example, each time a data point is selected in the performance-lifecycle cost plot, the probability density distribution of lifecycle values is produced. Plot-in-plot methods can be customized to a particular application, but even this simple example shows how useful plot-in-plot methods may be for representing multiple layers of data in two or three dimensions.
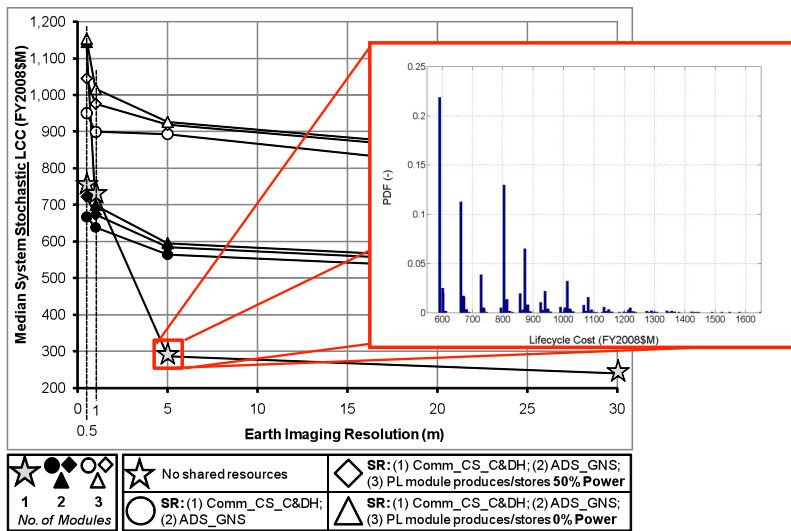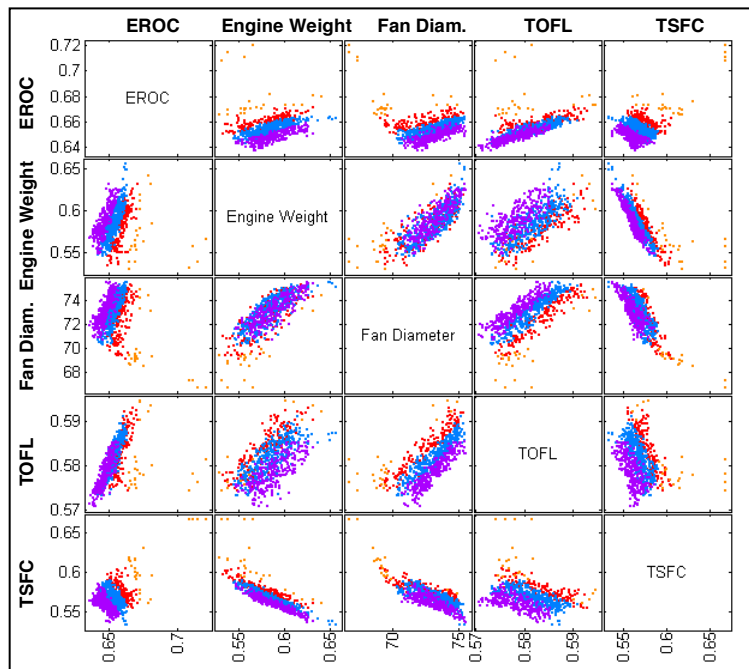

Figure A-7. An Example of a Plot-in-Plot Technique.

- **Carpet**

   Carpet plots are a series of individual scatter plots organized in a particular fashion, thus, they are a mixture of detailed and pattern plotting types. The organization of a carpet plot is that of a N-Squared (N^2) Diagram or Design Structure Matrix (DSM) where, given a set number of metrics, every possible combination of those metrics plotted against one another is explored (refer to Ref. [154,155] for an explanation of N^2 Diagrams and DSM's). This is specifically achieved by generating a matrix of scatter plots where the x-axis metric of the scatter plots remains consistent in each column of the carpet plot but, in each column, the y-axis varies by cycling through all of the metrics. Conversely, the y-axis metric of the scatter plots remains constant in each row of the carpet plot but, in each row, the x-axis varies by cycling through all of the metrics. An example of a scatter plot is provided in Figure A-8, which shows a carpet plot comparing data corresponding to several metrics of interest for the design of aircraft including: Estimated Return on Capital (EROC), Engine Weight, Fan Diameter, Takeoff Field Length (TOFL), and Thrust Specific Fuel Consumption (TSFC). The subplots along the diagonal are linear so they are emitted. As seen in Figure A-8, carpet plots provide a mixture of specific details about the data but also yield insights about the macroscopic trends in the data. For example, hypotheses about the invariance in the other metrics relative to a certain metric can be readily responded to using a carpet plot.


Figure A-8. An Example of a Carpet Plot.
(Source: RAVE Tutorial, Georgia Institute of Technology www.rave.gatech.edu)

197

- **Worlds-within-Worlds**

  Worlds-within-worlds plotting methods are similar to the plot-in-plot approach and are useful when the number of metrics to be visualized exceeds four. A simple example of this is a function, $f(x_1, x_2, x_3, x_4, x_5)$. In this case, one may start with a three-dimensional plot of $f(x_1, x_2)$. Then, assume there is a particular (x_1, x_2) point of interest, $f(c_1, c_2)$. Following the selection of this point, a new three-dimensional plot (*i.e.,* world) is generated at the point $f(c_1, c_2)$, but in the remaining three dimensions, (x_3, x_4, x_5). If there are multiple (x_3, x_4, x_5) value combinations that correspond to $f(c_1, c_2)$, then this next three-dimensional plot, or world will also be a surface. The advantage of worlds-within-worlds plotting methods is that the entire space of 3+ variables may be quickly explored by creating these worlds-within-worlds, assuming that one anchor point in each world is selected before generating the next world. This type of visualization is thus similar to plot-in-plot methods because it is active, that is, requires user feedback to continually create and adapt the visualization. An example of a world-within-world plot is shown in Figure A-9. Here, the first world is $f(x_1, x_2)$. Then the point function, $(x_1, x_2) = (0.845, 0.691)$ is selected, which corresponds to a $0.672\ f$ value. The next world is then generated at this point in the (x_3, x_4, x_5) space.
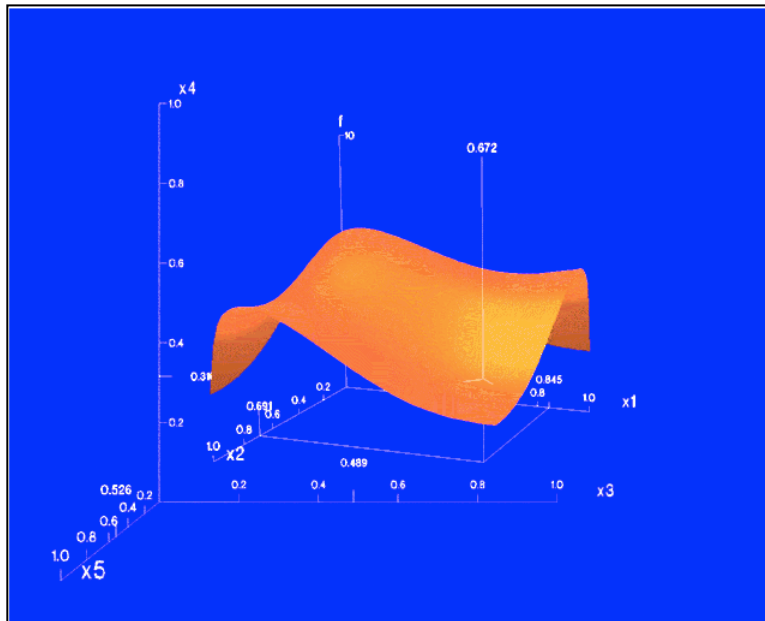

Figure A-9. An Example of a Worlds-within-Worlds Plot.

- **Hyperslices**

 Hyperslices characterize a multi-dimensional (hyper-spatial) function through a matrix of orthogonal two-dimensional slices (*i.e.,* contours) [156]. Hyperslices are an active visualization technique because they allow the user (observer) to manipulate and explore the data space by pointing and dragging a given two-dimensional contour, which, in turn, changes the other two-dimensional contours. A hyperslice specifically works by the user focusing on a particular contour and then moving the contour along its respective axes a certain distance. Once this is done, the contours in the same column and row as the contour of interest move an equal displacement. Thus, moving a contour is equivalent to resetting the range of interest for the two variables in the contour of interest and this is reflected where applicable in the hyperslice plot. Hyperslices also allow the user to rotate contours, which again causes analogous displacements and rotations in the other contours.　　　　　Figure A-10 shows a hyperslice characterizing the orbit of a point mass. In　　　　　Figure A-10, each contour may be manipulated, which in turn causes the others to move, effectively allowing the user to explore the contour space. This example along with another hyperslice example is found and explained in detail in Ref [156].
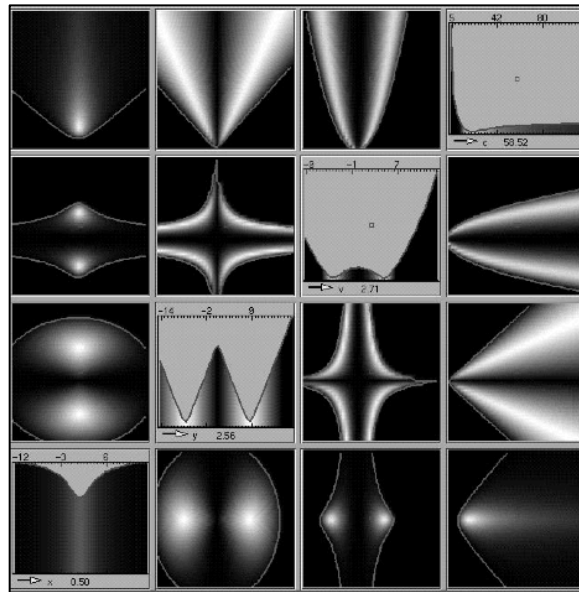
Figure A-10. An Example of a Hyperslice Plot.
(Source: Ref. [156])

199

Open-Source Visualization Software

There are several open-source software packages that can be used to visualize multi-dimensional information. While this list is not exhaustive, it provides a foundation for understanding how software developers have incorporated some of the aforementioned visualization methods into a user-friendly visualization tool.

- **Advanced Trade Space Visualizer (ATSV)** [157]

  ATSV is a software package developed at Penn State University, which allows users to build models, run experiments on those models, and ultimately explore and visualize the interaction amongst characteristics of the system of interest through hyperspatial visualization methods. The visualization approaches used in ATSV include: three-dimensional glyph plots, two-dimensional carpet plots, histograms, parallel coordinate plots, brushing, and preference shading/Pareto frontier generation. ATSV also has several different active visual steering capabilities: basic, active, and Pareto, which can be used to explore a multi-dimensional data set. Basic steering randomly populates the tradespace, thereby providing a broad view and exploration of the space. Attractor steering populates the tradespace in a local neighborhood around a user-selected point. And Pareto steering generates a Pareto front given user input preferences for maximizing or minimizing each objective or metric, thus allowing the user to explore along a data set's respective Pareto set.

- **Xmdv Tool** [158]

  The Xmdv Tool uses a variety of visualization techniques and has several unique capabilities. Visualization options within Xmdv include: carpet plots, star glyph plots, parallel coordinate plots, dimensional stacking, and pixel-oriented display. And the visualization capabilities include multivariate data manipulation, distortion techniques, screen brushing, and zooming.

- **Rave** [159]

  Rave is a visualization software package developed at Georgia Institute of Technology and is similar to ATSV in terms of capabilities. Rave allows for the visualization of multivariate data using 20+ different visualization techniques. Rave also uses data filtering methods to facilitate an exploration of the data space as well as generates user-defined multi-objective utility functions to find the optimum data point in a multivariate data space. Additionally, Rave can use surrogate models to

200

speed up the exploration and/or optimization of the data space. Lastly, Rave allows the user to generate Design of Experiment tables, which can then be automatically applied and used to explore the design space.

- **ModelCenter** [160]

    ModelCenter is developed by Phoenix Integration and has a variety of capabilities. The key attribute of ModelCenter is its ability to serve as a meta-model consisting of a series of individual models that are written in different programs (*e.g.,* Excel and Matlab) and then execute those models together. The obvious advantage of this is that a model does not have to be written in one program, which may be more desirable so that the model constituents can each be written (developed) in the most appropriate program. Specific capabilities and features of ModelCenter include a: server for analyses, Response Service Model (RSM) Toolkit, Monte Carlo Risk Analysis, Design of Experiments, and Geometry Viewer. ModelCenter's current base plug-in libraries (*i.e.,* programs it can integrate) include Excel, Matlab, and Mathcad. And ModelCenter's current modeling and simulation tools include Flames, Satellite Tool Kit (STK), and Extend. Lastly, ModelCenter's current costing tools/models include PRICE TruePlanning, SEER, and Automatic Costing Estimating Integrated Tool (ACEIT). In addition to these models, ModelCenter provides various visualization capabilities to contextualize the outputs of meta-models implemented in it.

APPENDIX B: THE DOE METHOD FOR RNAV/RNP APPROACHES

OVERVIEW

The objective of the Design of Experiment (DoE) method is to provide a preliminary search of the RNAV/RNP route space around a given airport and, for each potential route, evaluate its corresponding system outputs (see Section 7.3.2). The key is mapping a given route geometry to the resulting four system outputs of interest, and this is accomplished through surrogate models that relate a route's geometry directly to the outputs. The advantage of the surrogate models is that the system outputs can be computed in a fraction of a second for a given route rather than the 4-6 hrs required for each full analysis of a route via the NPIM (refer to Section 7.3.5 for a description of the NPIM). Thus, a very large number of potential RNAV/RNP routes can be evaluated with the DoE method and the best of these can then be analyzed in detail with the NPIM, based on user-defined criterion.

DOE SURROGATE MODELS

DoE surrogate models relate the geometry of a given approach route to the four direct system outputs considered in the Approach Procedures case study and, in doing so, allow for estimations of the outputs to be made rapidly for a given route. The governing assumption in developing these surrogate models is that aircraft fly the same descent profile (*i.e.,* altitude, thrust, and speed vs. ground track distance profiles) based on distance from the runway of interest.

- The **surrogate model** for the outputs of **fuel burn, and flight time** are direct correlations with ground track distance. These correlations were derived using the system outputs corresponding to several ILS routes into Boston-Logan airport (BOS) determined from previous analyses conducted by the author; BOS is the airport of interest in this case study. The resulting linear surrogate models form a set of equations for these outputs dependent on the ground track distance of a given route; these are summarized in Equation 16 along with the R^2 values from the linear regressions.

Equation 16

$$FB = 7.80d_{track} + 135.13 \quad R^2 = 1.00$$
$$FT = 0.003d_{track} + 0.17 \quad R^2 = 0.89$$

  In Equation 16, *FB* and *FT* are the fuel burn (gal) and flight time (hrs), respectively. As seen in the equation, these two system outputs are highly correlated to ground track distance, d_{track}, and they can thus be readily approximated for a given approach route geometry. In addition to creating a surrogate model for these outputs, given the valuation approach used in this case study (see Section

7.3.3), a surrogate model of operational costs (*i.e.,* the cost of fuel and time) can also be created; this will serve a unique purpose in the DoE method as will be described later. Equation 17 provides the resulting operational cost surrogate model.

Equation 17

$$C_{Ops} \quad = \quad 22.56d_{track} + 549.46 \quad R^2 = 0.99$$

In Equation 17, C_{Ops} is the cost of the flight path in United States Dollars dependent on ground track distance. As seen by the R^2 value in Equation 17, it is highly correlated with ground track distance.

- The **surrogate model** for **population noise exposure** is the number of people in the *critical* population noise corridor along a given route. The critical noise corridor is the area adjacent to a route's respective ground track a distance of x nm on either side of the route until aircraft touchdown. The portion of an approach creating the critical noise corridor is that during final descent, since this is when population noise exposure at critical levels (*i.e.,* 60+ dB) is the highest. The basis for the population noise exposure surrogate model is therefore that communities within a certain proximity of the final descent portion of an approach will experience the highest noise exposure. And, thus, the number of people in a critical noise corridor effectively predicts the ultimate population noise exposure at critical levels. The key to this surrogate model is defining how large the buffer should be because this is very aircraft and procedure dependent, so the buffer value must be based on experience. Preliminary research conducted by the author suggests that a 2nm buffer on either side of a route's final descent phase captures the communities that will be exposed to the most critical noise, so this effectively creates a 4nm wide critical population noise exposure corridor during an aircraft's final descent. However, this assumption, and more generally this surrogate model for population noise exposure needs to be refined through further development and testing.

- A **surrogate model** for the **throughput** system output is not required because in this case study throughput is an exogenous *input* into the Noise and Performance Impact Model (see Section 7.3.5). Given this input, the traffic density along a given route is computed. Therefore, in designing new routes, the throughput system output is an input.

The previously described surrogate models allow for the rapid evaluation of a given approach route in terms of the four system outputs of interest (note that these outputs only include the direct outputs considered in the Approach Procedures case study). The corresponding DoE method is summarized in Figure B-1 and the formal steps of the method are discussed thereafter.
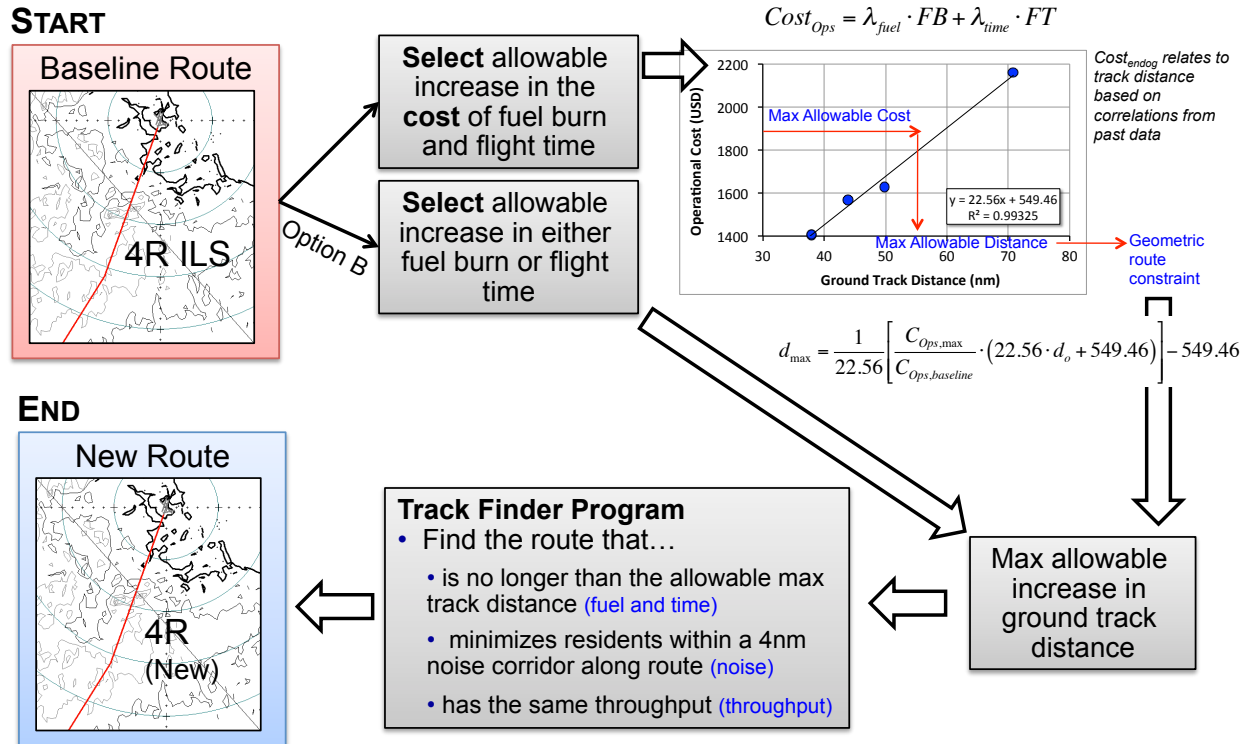
Figure B-1. The Design of Experiment Method.

1. **Select a baseline route:** this baseline route will serve as the comparison basis in the DoE method. When designing new RNAV/RNP routes, a typical choice for the baseline route is the existing ILS approach corresponding to the runway of interest.

2. **Select a constraint option:** Potential routes can be constrained by Option A or Option B, which dictates the allowable system output range for fuel burn or flight time. If Option A is selected, the user sets an allowable threshold for the change in operational cost (see Equation 17) relative to the baseline route. Conversely, if Option B is selected, then a threshold on one of the either the fuel burn or flight time system outputs is set and this effectively sets a threshold on the other system outputs since their respective surrogate models all depend on ground track distance.

If it is desirable to only consider new routes that have less fuel burn and flight time relative to the baseline route, then the allowable change in flight path cost (Option A), or allowable change in one of the system outputs should be less than that of the baseline route (*i.e.,* a negative change). The converse is true if new routes are allowed to exceed the fuel burn and flight time of the baseline route; note that this situation is often needed in order to reduce population noise exposure relative to a current ILS procedure.

3. **Determine the allowable ground track distance:** since the surrogate models relate fuel burn and flight time to ground track distance, once Option A or B is used to constrain a system output (or the cost of the outputs), this can be translated into an effective constraint on the maximum allowable ground track distance of new routes relative to the baseline route.

4. **Track Finder Program:** given the maximum allowable ground track distance, the track finder program then searches the ground track route space around the airport/runway of interest and finds the route that: (a) is no longer than the maximum allowable ground track distance, which ensures that the fuel burn and flight thresholds are not exceeded; (b) minimizes the number of residents within the *critical* noise exposure corridor; and (c) has the same throughput as specified by the analyst in the Tradeoff Analysis Framework.

The corresponding output of the track finder program is the route that minimizes the number of residents in the critical noise exposure corridor and that does not violate the fuel burn, flight time, and throughput constraints set by the user of the DoE method. This route is then analyzed in full by the NPIM discussed in Section 7.3.5.

From a practical perspective, in terms of implementing the aforementioned DoE method, in order to search the ground track space with the Track Finder Program, it must be discretized into a latitude/longitude grid ending with the latitude/longitude of the runway of interest. Additionally, the grid should account for any requirements in terms of minimum allowable curvature in approach routes and required straight-in legs before landing. Intuitively, the finer the latitude/longitude grid, the more tailored routes can be, but the longer the time required to execute the DoE method.

APPENDIX C: PCA OF THE REMOTE SENSING MISSION CASE STUDY RESULTS

Appendix C compares the PCA of the fractionated spacecraft results corresponding to the three different ConOps schemes presented in the first case study (see Section 7); this comparison is provided in Figure C-1 - Figure C-3. The interesting insights to be gained from these schemes arise from comparing the relative differences amongst the plots in this appendix.

The On-Demand and Threshold schemes provide very similar relative tradeoffs amongst the system outputs considered. Additionally, in all three ConOps schemes, SLCC is nearly neutral to TWAP and Revenue, which are always nearly perfect complements. This suggests that TWAP and Revenue remain correlated and relatively independent of SLCC no matter what redeployment/replenishment scenario used for fractionated spacecraft, thus supporting the general independence between TWAP and SLCC as reasoned in Section 8.4.4. The remaining observation is that in the On-Demand and Threshold schemes, TWAP/Revenue are fairly complementary with ToS, but in the Predicted scheme, TWAP/Revenue are almost perfectly complementary with ToS. The reason for this is that the ToS is larger with the Predicted

Figure C-1. PCA (On-Demand).

Figure C-2. PCA (Predicted).

Figure C-3. PCA (Threshold).

replenishment scheme (as compared to the On-Demand and Threshold scenarios), and thus a larger contributor to TWAP, since ToS is effectively a multiplier on TWAP; hence, these tradeoff dimensions are more closely aligned in the Predicted Replenishment scheme. Therefore this result substantiates the
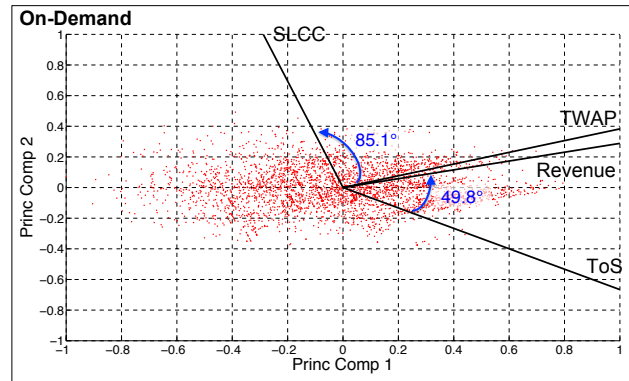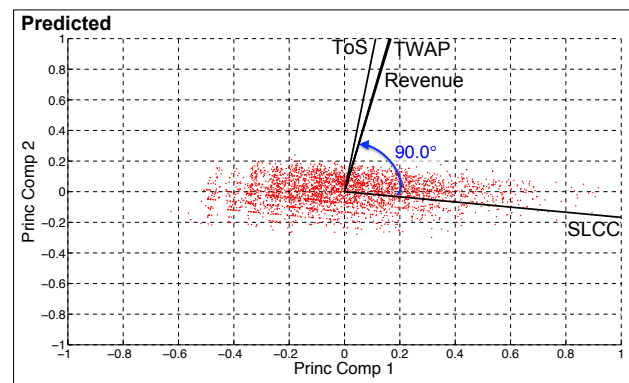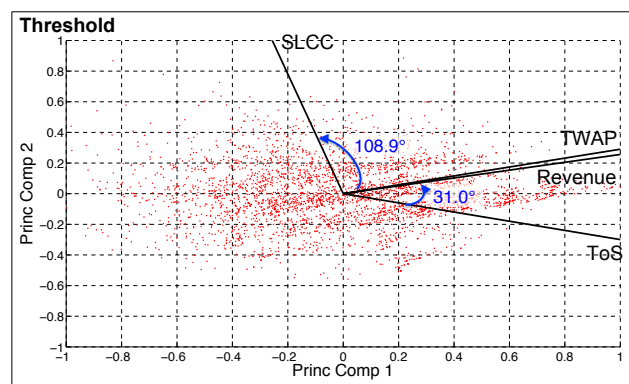
207

intuition that the stronger the dependency between two metrics, the closer in proximity they will be in the PCA space and, hence, the closer they are to becoming complements.

APPENDIX D: SPACECRAFT OPERATIONAL HISTORIES

This section compares the operational histories for the fractionated spacecraft examined in the remote sensing mission case study (see Section 7). This comparison demonstrates the underlying behavior of spacecraft relative to each of the ConOps scenarios (i.e., replenishment strategies) considered. It is important to note that fractionated spacecraft initial builds are not started until the minimum acceptable enabling technology performance is achieved; hence, the initial development time for a spacecraft may be longer than the assumed 5 year initial build time. Figure D-1 - Figure D-3 show representative operational histories of the fractionated architecture relative to each ConOps scheme. As seen in the figures, the operations span the assumed 30-year time-window, the periods of active payload operation are highlighted in blue, and the corresponding on-orbit payload performance is indicated by the y-axis value. In the On-Demand scheme (see Figure D-1), there are punctuated periods of downtime since in this scheme module rebuilds only begin after an observed on-orbit failure. Conversely, payload continuity is
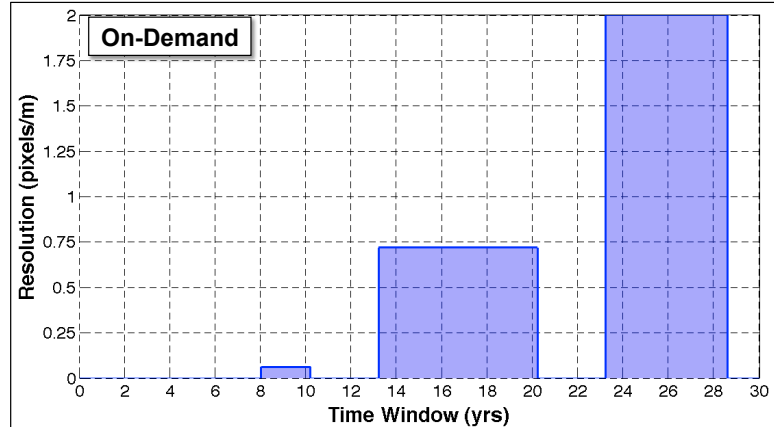

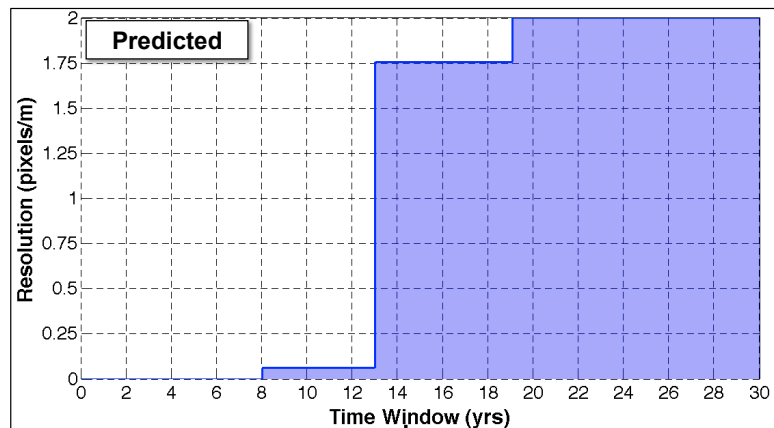**Figure D-1.** Lifecycle Performance (On-Demand).

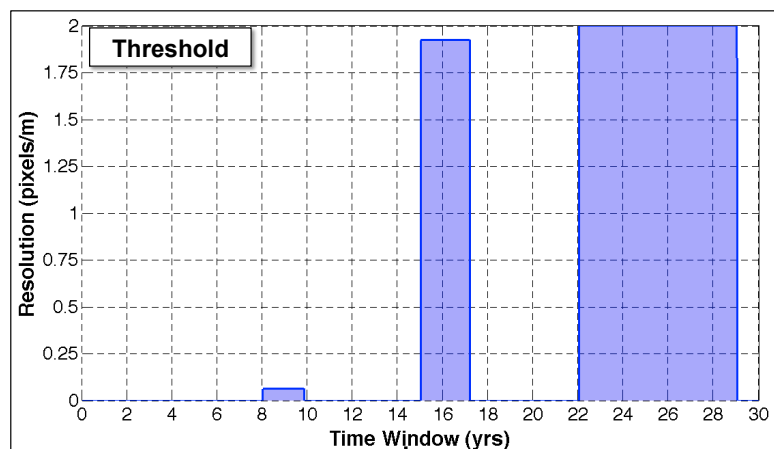**Figure D-2.** Lifecycle Performance (Predicted).

Figure D-3. Lifecycle Performance (Threshold).

209

maintained with the Predicted replenishment scheme as shown in Figure D-2. Here, the modules are immediately replaced after they fail, thus maintaining payload continuity throughout the time window. The last replenishment scenario is the Threshold scheme. As seen by the representative operational history shown in Figure D-3, modules are not rebuilt unless there are improvements in the enabling technologies; hence, each payload module redeployment increases the spacecraft performance. The result is that the operational history of the Threshold scheme is very similar to that of the On-Demand scheme (this is reasoned in more detail in Section 8.5). As can be seen in Figure D-1, the downtimes with the On-Demand scheme are, on average, shorter than that of the Threshold scheme, since in this latter scheme enabling technology improvements dictate the replenishment timing, which happen to be on average slightly longer than the 3-year module rebuild time assumed in this case study; the reasoning for this is based on the assumption used in the analysis as discussed in Section 8.5.

The representative examples of fractionated spacecraft operational histories shown in Figure D-1 - Figure D-3 support the value proposition conclusions made in the remote sensing mission case study in Section 5.6.4. Namely, that the average value delivered by the On-Demand and Threshold schemes is very similar, which is indicative of the very similar operational histories shown in Figure D-1 and Figure D-3. And, in addition, given the much higher time of payload service exhibited with the Predicted scheme, as shown in Figure D-2, the value of this scheme leads to consistently higher fractionated spacecraft value than that realized when using the other two schemes.

210